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Innovations in Defense Acquisition Auctions: Lessons Learned and Alternative Mechanism Designs

21 February 2008

by

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Abstract

Since 1997, the Department of Defense (DoD) has shown increasing interest in using reverse auctions, particularly electronic reverse auctions, to purchase a wide range of products and services. The research describes DoD's experience with acquisition auctions, identifying the characteristics of the buyers, sellers, and the products/services exchanged through auctions. In general, reverse auctions have been limited to procurement actions involving relatively standard price-driven commercial products—products typically purchased through traditional competitive markets. It appears that DoD has substituted reverse auctions for the market research required in the standard DoD procurement processes; the auction service providers are replacing federal procurement agents in advertising the procurement action and soliciting bids from competing suppliers.

Drawing on this background, this research examines auction mechanism(s) that appear appropriate for the defense acquisition environment. Two specific auction designs are explored. The first is a two-stage Iterated Information Aggregation Auction (I^2A^2) involving multiple product characteristics—including price—that are specified as part of the auction bidding process. In the I^2A^2, the first stage acts as market research for gathering information dispersed across the decentralized contractor base to establish characteristic weights to evaluate proposals in the second stage. The research showed significant potential performance improvements when decentralized trade-off information is centralized through the I^2A^2 mechanism.

The second auction mechanism involves situations where the quality of fit between the buyer and seller affect the transaction's value (e.g., synergy between an author and an editor, etc.). This analysis explores the impact of asymmetric information on the mechanism's design. The research developed optimal mechanisms for transactions where both parties know the quality of fit and transactions in which only one party (the buyer or sellers) know the quality of fit.

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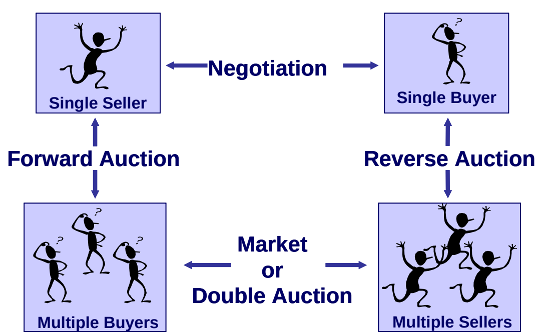
I. Introduction

The economy has developed several mechanisms to govern the interactions between buyers and sellers.[1] Traditional markets are most effective when there are many potential buyers and sellers and when products are relatively standardized. In traditional markets, competition between both buyers and sellers ensures that the market establishes an efficient price to balance supply and demand. Bargaining generally characterizes situations where markets are thin and there are few buyers and sellers. Forward auctions are increasingly used in cases in which there is only one seller and several buyers. This trend is evident with the explosion of online auctions, such as e-Bay. Reverse auctions involve a single buyer and several sellers.



The Department of Defense (DoD) participates in transactions that involve several of these situations. As a consumer of specialized defense products, DoD operates as single buyer with any where from a single to several potential suppliers, depending on the uniqueness of the defense product. As a consumer of standard commercial commodities, such as pencils and paper, it participates in markets with many buyers and sellers, though the size of defense purchases often makes DoD an atypical consumer in these markets. As a result, DoD should be expected to exploit the

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[1] A mechanism is the set of rules that govern the interactions between parties in a relationship; in this application it is the set of rules that govern the interactions between buyers and sellers in defense acquisition.

full range of transaction mechanisms, from standard market interactions to auctions and bargaining.

Historically, the DoD acquisition process, and the federal government in general, emphasize market transactions and bargaining. The federal government has developed a specialized set of rules to govern these interactions (the *Federal Acquisition Regulations* or the *FAR*); DoD has added its own set of rules to adapt the *FAR* to Defense applications (the *Defense Federal Acquisition Supplement*, or the *DFARs*).

Since 1997, DoD has shown increasing interest in using auctions to exploit the full range of transaction mechanisms. Prior to 1997, auctions were largely precluded by the *FAR*; however, the 1997 *FAR* rewrite removed wording that prohibited auctions. As discussed below, procurement officials now view the *FAR* as supporting federal procurement auctions. As a result, reverse auctions, particularly electronic reverse auctions, have been expanding in use across the federal government and DoD. Several providers offer electronic reverse auction (e-RA) services and many responded to requests for information for this research. However, only two providers contributed detailed data: FedBid, Inc. (FedBid), and the US Army Auction and Valuation Engine (USAAVE). USAAVE was developed by MOAI CompleteSource and is used by the Army Communications and Electronics Command (CECOM) Acquisition Center.[2]

Given the transaction mechanism hierarchy described above, defense acquisition auction applications should typically involve DoD as a single buyer facing several potential sellers through a reverse auction. Atypically, many early DoD acquisition auctions involved more standard commercial products and services with several competing sellers. For example, information technology equipment, software and supplies represented approximately 50% of the auctions between FY2002 and FY2007,

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[2] FedBid and USAAVE data was gathered by Whitney Brown, Capt., USAF and Lana Ray, Capt., USAF in support of this research project. Their detailed results are reported separately in Brown and Ray (2007).

in terms of both value and number of auctions, as conducted by FedBid, a large defense electronic auction house.[3] These early defense auction applications involve relatively straightforward auction designs and were credited with significant DoD cost savings (FedBid estimates 8.8% savings for DoD and 14.4% savings for the rest of the federal government between FY2002 and FY2007; USAAVE, another defense electronic auction house, estimates 31.6% savings between FY2000 and FY2007[4]).

Commensurate with the explosion of auctions in practice, there has been an explosion in theoretical and experimental work on auctions. As a result, there is a broad base of auction mechanisms from which to choose; auction mechanism design is increasingly tailored to the specific situation at hand. Some important design characteristics include the number of sellers, the number of items being purchased, the number of items that can be purchased from each seller, the number of markets (auctions) in which sellers simultaneously participate, etc. The more standard auction theory does not address these more stylized circumstances.

Based on developments of auction theory, it is important to consider how auctions have been, or could be, applied to defense acquisition. In considering this application, imperfect and asymmetric information are pervasive themes across all of DoD’s transactions. Asymmetric information might take several forms: imperfect information about potential sellers’ prices or costs; imperfect information about product quality or even DoD’s optimal level of quality, if the trade-offs between cost, performance and schedule are unclear ex ante; and uncertainty about the quality of the fit between DoD and the supplier, where the fit between buyer and seller significantly affects the transaction’s value. This research will address how DoD might tailor its interaction with contractors to exploit auction design and address information asymmetries.

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[3] Brown and Ray (2007), Appendix C.

[4] Ibid., Appendices A and B.

This research considers three related issues, as appropriate. The research will begin by describing the Defense Department's experience with acquisition auctions, which will identify the characteristics of the buyers, sellers, and the products/services exchanged through auctions. It will indicate the characteristics of the auction environment and whether auctions are being applied in the most appropriate instances.

Drawing on past experience, the research will examine auction mechanism(s) that appear appropriate for the defense acquisition environment. Two specific auction designs will be explored. The first is a two-stage Iterated Information Aggregation Auction (I^2A^2) involving multiple product characteristics—including price—that are specified as part of the auction bidding process. In the I^2A^2, the first stage acts as market research or gathering information dispersed across the decentralized contractor base to establish characteristic weights to evaluate proposals in the second stage. The second auction mechanism involves situations where the quality of fit between the buyer and seller affect the transaction's value (e.g., synergy between an author and an editor, a mentor and a protégé, etc.). This analysis will explore the impact of asymmetric information on the mechanism's design, including situations in which both parties are fully informed about the quality of the match and situations in which only the buyer (seller) has perfect information. Finally, the research will develop simulation evidence demonstrating how the auction mechanisms perform in the defense acquisition environment.

II. Auction Theory

A. Auction Characteristics

As mentioned above, auctions are an appropriate mechanism to set prices in market transactions when there is either a single seller and several buyers (forward auction) or a single buyer and several sellers (reverse auction). Within these two broad categories, potential auction designs can be further sub-divided into open/sequential bid auctions and sealed/simultaneous bid auctions. In open/sequential bid auctions, bidders or their agents are present during the auction—either physically or virtually—to monitor the auction's progress and bid as appropriate. Bidders in sealed/simultaneous auctions need not be present during the auction; instead, they submit bids prior to the auction and all bids are opened simultaneously.[5]

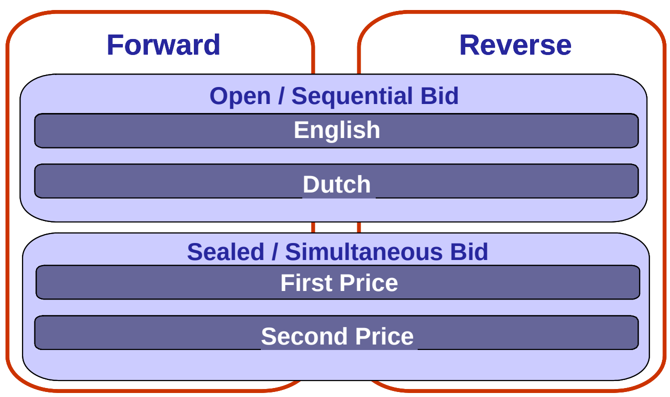

Figure 1. Alternative Auction Structures

In an English auction, bidders successively call out bids, which either raise the current price in a forward auction or lower the price in a reverse auction. Bidders remain in the auction until the current price surpasses their value, at which point they

[5] For a more detailed description of auction types see Brown and Ray (2007), chapter II. For a general discussion of auction theory see Campbell (2006), Kambil and vanHeck (2002), Klemperer (2002), McAfee and McMillan (1987) and Shubick (1983). This section draws from these references

voluntarily drop out. The auction continues until only one bidder remains (the highest bidder in a forward auction and the lowest bidder in a reverse auction). The last bidder wins the auction at a price equal to the value of the last excluded bidder (the second highest value in a forward auction and the second lowest value in a reverse auction). The English auction is the most commonly envisioned auction mechanism and is used routinely by many private auction houses to sell antiques, artwork, etc.

In a Dutch auction, the price starts at a price well in excess of the expected closing price (high in a forward auction and low in a reverse auction). The auctioneer then adjusts the price until a bidder signals a willingness to accept. Dutch auctions have been used in Holland to sell tulips, amongst other things. The item is awarded to the first bidder at the price bid.

As mentioned above, bidders submit their bids prior to the auction in a sealed/simultaneous bid auction. These bids are sealed (i.e., private and unknown to other bidders). The bids are opened simultaneously and the winner is determined (highest bid in a forward auction and lowest bid in a reverse auction). In a first-price sealed-bid auction, the final price is determined by the winning bid (the winner pays/receives what it bid). In a second-price sealed-bid (Vickery) auction, the price is determined by the first excluded bid (the second highest bid in a forward auction and the second lowest bid in a reverse auction) (Vickery, 1961). First-price sealed-bid auctions are the traditional sealed-bid auctions used for federal procurements.

B. Bidding Strategies

Table 1. Auction Bidding Strategies and Outcomes

Auction	Strategy	Outcome
English	Bid Up to True Value	Highest Bidder Wins at 2nd Price
Dutch	Trade-Off Between Risk and Return	????? – No Bids Above Value
First-Price Sealed-Bid	Trade-Off Between Risk and Return	????? – No Bids Above Value
Second-Price Sealed-Bid	Bid True Value	Highest Bidder Wins at 2nd Price

Different auction mechanisms elicit different bidding behavior and potentially different auction outcomes. The bidding strategy in the English auction is straightforward: continue bidding as long as the current price provides a positive surplus value (profit); drop out of the bidding once the price no longer provides a positive surplus value. As such, the highest-valued bidder will win a forward English auction at a price equal to the second-highest bidder (equivalently, the lowest-priced supplier would win a reverse English auction at the price of the second-lowest-priced supplier).

The optimal bidding strategy in a second-price sealed-bid is also straightforward: always bid your true value. There is no potential gain from bidding either above or below your true value, but there is a potential loss. Consider a forward auction in which my expected value for the item being sold is $100. Recall I pay the second-highest bid (first-excluded bid) if I win this auction. Suppose I bid $110 and the second-highest bid is $90. I would win the auction and pay $90; my surplus (profit) is $10. However, I would still win and earn the same surplus if I bid $100. Alternatively, suppose I bid $110 and the second-highest bid is $105. I would win the auction but pay $105, losing $5. I would not win this auction if I bid $100. In other words, there is no gain from overbidding in auctions that provide a positive surplus; however, overbidding can lead to winning an auction that earns a negative surplus.

The argument against underbidding is similar. Suppose I bid $90 and the second-highest bid is $80. I would win the auction and pay $80, earning a $20 surplus. However, I would still win and earn the same surplus if I bid $100. Alternatively, suppose I bid $90 and the winning bid is $95. I lose the auction and forego a potential $5 surplus; I would win the auction and earn the $5 surplus if I had bid $100. Thus, there is no gain from underbidding. Underbidding does not increase my surplus if I win the auction, but it may preclude me from winning an auction that would provide a positive surplus.

With a dominant strategy of truthfully revealing actual value, a second-price sealed-bid auction has the same expected outcome as an English auction: the auction is won by the bidder with the highest (lowest) value in a forward (reverse) auction at a price equal to the first-excluded bid—the second -highest (lowest) price in a forward (reverse) auction. In theory, these two auction structures are equivalent.

The optimal bidding strategies are a bit more complicated in Dutch and first-price sealed-bid auctions. When participants submit their bids in these auction formats, they do not have any information about the bids submitted by other participants. Furthermore, their bid determines both their probability of winning and their surplus (profit) if they win. As a result, bidders face a trade-off between risk and return in selecting their bids. In a first-price sealed-bid auction, I maximize my probability of winning an auction by bidding my actual value, but that sacrifices all surplus value. As I adjust my bid to increase my surplus, I reduce my probability of winning. If I am neutral in my risk preferences (neither avoid nor seek out risk), I will select the bid that maximizes my expected surplus value. In a forward (reverse) auction, this strategy involves shading my bid below (above) my actual value. If I am risk averse, I will bid closer to my true value to reduce my risk (but sacrificing my expected surplus—I am paying to reduce risk).

The Dutch auction is equivalent to the first-price sealed-bid auction. As the price falls in a forward Dutch auction, I maximize my chances of winning the auction if I bid to accept the price as soon as it equals my true value; however, that sacrifices all surplus value. If I let the price continue to fall, it increases my surplus but decreases my probability of winning (increases the probability someone else will bid to accept the current price). If risk-neutral, I want to bid when the auction reaches the price that maximizes my expected surplus value. As above, this involves shading my bid below (above) my actual value in a forward (reverse) auction.

The revenue equivalence theorem demonstrates that all four auction designs have the same expected price (seller revenue) with risk-neutral bidders and a few other typically applicable characteristics (many bidders who all have the same distribution of potential values, individual values that are independent across participants, and payments that are a function of bids alone). To motivate revenue equivalence while avoiding a formal mathematical proof, suppose all bidders are risk neutral and fully informed about everyone's true value. How would I bid in a forward first-price sealed-bid or Dutch auction. If I were the highest valued bidder, I would bid a price equal to the second-highest value; the auction would have the same outcome as an English or second-price sealed-bid auction. No one else could outbid me without losing money.

What if I do not have perfect information about the other bidders' values? If I think I am the highest valued bidder, my goal is to guess the second-highest value and set my bid equal to this estimate (I might allow for some margin of error if I am risk averse). If bidders guess on average, and there is no reason to expect rational bidders to systematically over- or under-estimate the range of values, then all auctions are revenue equivalent on average. This outcome is the basis for claiming revenue equivalence.

C. Additional Auction Mechanisms

There are several additional auction designs that have evolved to address more unique situations. A few will be mentioned briefly here, including multi-item auctions, multi-attribute auctions, combinatorial auctions, and hybrid auctions. Multi-item auctions involve selling or buying multiple units of the same item, generally from multiple bidders.

These auctions can determine a single price for all transactions or different prices for each transaction. Multi-attribute auctions typically involve transactions in which the buyer is interested in several attributes of the item being sold. For example, a federal auction for spare parts might include attributes such as price, delivery schedule and technical quality. Different bids would involve different combinations of these attributes and the government would determine the preferred bid by weighting the attributes according to the government's preferences. Combinatorial auctions are typically the mirror image to multi-attribute auctions; they are forward auctions in which buyers offer monetary bids for items that have multi-dimensional characteristics.

Finally, there are a variety of hybrid auctions. One hybrid of interest, used in many electronic auction sites, such as E-Bay, is the English auction with proxy bidding. Proxy bidding allows participants to specify the maximum they are will to pay for the item in question. For example, suppose I am willing to pay up to $100 for an item being auctioned; the current price is $40 and the minimum bid increment is $2. With proxy bidding, I would specify $100 as my maximum bid. This maximum is private information. Proxy bidding would enter my bid as $42 (the current price plus the minimum bid increment). If another bidder enters the auction and raises the bid to $50, my proxy bid would automatically increase to $52. This would continue until either I win the auction or the winning price exceeds $100 (I do have the option to increase my proxy bid).

Proxy bidding essentially converts a familiar auction format, the English auction, into a less familiar format, the second-price sealed-bid auction. With this type of proxy bidding, the optimal strategy is to specify my true value, just as in a second-price sealed-bid auction.

In addition to the general structure of the auction mechanism design, there are several design characteristics that influence an auction's performance. Some of these features include reserve prices/minimum bids, minimum bid increments, entry fees, auction ending rules, bidder information, etc. Brown and Ray (2007, chapter II) provide a brief introduction to these characteristics, as well as others. It is important to note that these characteristics can affect an auction's performance, and they are important to consider in determining an optimal auction design. However, detailed discussion of these attributes is beyond the scope of this research.

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III. Reverse Auctions in the Federal Government

A. Federal Regulations Affecting Procurement Auctions

If auctions are to be used in the federal procurement process, they must satisfy all the relevant federal rules and regulations. This discussion, adapted from Brown and Ray (2007, Chapter 3), briefly summarizes the relevant rules and regulations.

1. Federal Acquisition Regulation and Defense Federal Acquisition Regulation Supplement

The primary documents regulating the defense acquisition process are the *Federal Acquisition Regulation* (*FAR*) and the *Defense Federal Acquisition Regulation Supplement* (*DFARS*). The *FAR* is the general guidance covering all federal acquisitions; the *DFARS* is one of several supplements that specifically tailors the federal policies to the defense sector, typically imposing additional restrictions and requirements.

The *FAR* specifically prohibited auctions prior to 1997; in particular, *FAR* Part 15,610(e)(2) prohibited:

> Auction techniques such as—
>
> Indicating to an offeror a cost that it must meet to obtain further consideration;
>
> Advising an offeror of its price standing relative to another offeror (however it is permissible to inform and offer that its cost or price is considered by the Government to be too high or unrealistic); and otherwise furnishing information about other offerors' prices.

However, this language was eliminated in 1997, and now *FAR* Part 1.102 (d) and *FAR* Part 4.502 (a) are considered to authorize federal procurement auctions. These *FAR* sections state:

> *FAR 1.102 (d):* In exercising initiative, Government members of the Acquisition Team may assume if a specific strategy, practice, policy or procedure is in the

best interests of the Government and is not addressed in the FAR, nor prohibited by law (statute or case law), Executive order or other regulation, that the strategy, practice, policy or procedure is a permissible exercise of authority.

FAR 4.502 (a): The Federal Government shall use electronic commerce whenever practicable or cost-effective.

2. Buy American Act

The Buy American Act (BAA) restricts the purchase of foreign-produced end-products. While e-RA may facilitate participation by foreign suppliers, the BAA restrictions still apply. The BAA provision and clause are included in all solicitations and contracts, and the contractor will be held responsible for any violations. Similarly, the contracting officers must do their part to ensure the products procured through federal auctions adhere to the Buy American Act.

3. Procurement Integrity Act

The Procurement Integrity Act prohibits disclosure of one contractor's proposal information to other competitors. *FAR* 15.306(e)(3) similarly stipulates that the government may not "reveal an offeror's price without that offeror's permission." This would seemingly preclude reverse English auctions, or any other auction mechanism that publicizes the participants' bids. Typically this is resolved by including language in the solicitation stating that participation implies consent to reveal anonymous price data, though there is some debate about whether participation can imply consent.

4. Socio-Economic Concerns: Small and Disadvantaged Businesses

Congress believes that "the security and well-being [of the nation] cannot be realized unless the actual and potential capacity of small businesses is encouraged and developed" (15 USC 631, 2006). To promote small businesses in the federal procurement process, the Small Business Act, Armed Services Procurement Act, Federal Property and Administrative Services Act, section 7102 of the Federal Acquisition Streamlining Act of 1994, and Executive Order 12138, May 18, 1979, all incorporate guidance regarding the use of small and disadvantaged businesses (*FAR* 19.000).

Accomplishing this objective requires contracting officials to seek qualified small businesses and involve them in the procurement process. This is accomplished through a variety of outreach mechanisms to identify interested businesses, inform them about procurement opportunities and help them navigate the federal procurement regulations and procedures. It is also supported by dividing larger procurement lots into sizes more consistent with small business capabilities (which is authorized by *FAR* 19.202-19(a)).

To further support this objective, *FAR* 19.5—Set Asides for Small Business—mandates that all requirements for supplies and services between $3,000 and $100,000 be designated specifically for small businesses as long as there is a reasonable expectation of two or more responsible small businesses. This is further applied to requirements for services and supplies over $100,000, again assuming a reasonable expectation of two or more responsible small businesses.

Electronic reverse auctions are compatible with these objectives as long as small businesses have the technology and knowledge required to participate. The required technology includes access to a computer and to the Internet. This technology is already required to participate in the traditional federal procurement process; *DFARS* 252.232-7003, Electronic Submission of Payment Requests—March 2007, requires all contractors to submit their invoices electronically, via one of several Internet/web-based invoicing systems.

The expertise to participate in an electronic reverse auction is available to both contractors and contracting officers through a Defense Acquisition University continuous learning module (CLC 031: Reverse Auctions); a 22-page electronic General Services Administration (GSA) Reverse Auction User's Guide (GSA 2002), and Internet resources developed by the US Army Communications-Electronics Command

(CECOM, n.d.), the US Navy's Supply Systems Command (NAVSUP, n.d.), The US Air Force (2006) and several other federal agencies. Reverse auction service providers, such as FedBid, also provide training.

In many respects, e-RA may facilitate small business participation. For example, when a procurement request is designated as a small business—service-disabled veteran-owned or other set-aside—Fedbid focuses its solicitation on the relevant category of businesses, sending the solicitation to every registered vendor in that industry, thereby satisfying the set-aside requirements. FebBid will also seek additional qualified vendors if there are insufficient responses to the solicitation (FedBid, 2007b).

In general, e-RAs have been well received. There have been some complaints that auctions drive prices below those negotiated in Basic Purchasing agreements (BPAs) or Government-wide Acquisition Contracts, and some argue that the final auction prices are too low to provide a reasonable small business profit (Stever, 2007). However, as indicated in the auction theory section, complaints about excessively low prices should be expected for all but the winning bidder. If the price was still attractive to multiple vendors, they would have continued bidding. On balance, vendors have accepted e-RAs. Only three protests have been filed with GAO to date and none were resolved in the vendor's favor[6] (GAO 2005; GAO, 2001a, GAO, 2001b).

B. Electronic Reverse Auctions: Defense Department and Other Federal Agencies

As mentioned above, several providers offer electronic reverse auction (e-RA) services. Two providers were able to supply detailed data for this research: FedBid, Inc. (FedBid) and the US Army Auction and Valuation Engine (USAAVE).[7] This data

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[6] For more detailed discussion of these protests, see Brown and Ray (2007, Chapter 3).

[7] FedBid and USAAVE data was gathered by Whitney Brown, Capt., USAF and Lana Ray, Capt., USAF in support of this research project. Their detailed results are reported separately in Brown and Ray (2007).

shows the volume of transactions completed through electronic reverse auctions. Table 2 summarizes the auctions conducted by FedBid over the period FY2002—FY2007 and by USAAVE over the period FY2000 and FY2007 (Brown and Ray, 2007, Appendix B).

The FedBid and USAAVE data summarized in Table 2 also estimated the savings attributable to the e-RA procurement process. In both cases, FedBid and USAAVE estimated their savings by comparing the actual contract price to the ex ante independent government cost estimate. Using this benchmark, the savings attributed to e-RAs are significant: 12.7% overall for FedBid, including 8.8% for DoD procurements and 14.4% for the other federal agencies, and 31.6% for USAAVE.

Table 2. FedBid and USAAVE Auction Results
(Adapted from Brown and Ray, 2007)

FedBid Cost Savings by Federal Agency (FY2002 - FY2007)					
Government Agency	**Number of Awards**	**Independent Government Estimate**	**Final Award Price**	**NET Savings in Dollars**	**NET Savings in Percentage**
FEDERAL GOVERNMENT	**18,401**	**$1,187,932,046**	**$1,037,440,499**	**$150,491,548**	**12.70%**
DEPARTMENT OF DEFENSE	**5,932**	**$351,179,597**	**$320,444,507**	**$30,735,089**	**8.80%**
Department of the Army	3,101	$146,222,796	$132,698,678	$13,524,119	9.20%
Department of the Air Force	316	$58,553,765	$53,909,867	$4,643,898	7.90%
Department of the Navy	1,710	$70,127,231	$63,805,400	$6,321,831	9.00%
Other DoD Agencies	805	$76,275,804	$70,030,563	$6,245,241	8.20%
CIVILIAN AGENCIES	**12,166**	**$829,655,257**	**$710,525,334**	**$119,129,923**	**14.40%**
Department of Commerce	612	$48,030,428	$43,332,910	$4,697,519	9.80%
Department of Homeland Security	1,251	$253,431,462	$204,639,316	$48,792,146	19.30%
Department of Human Health Services	213	$46,662,044	$36,555,135	$10,106,908	21.70%
Department of Interior	18	$340,395	$302,297	$38,099	11.20%
Department of Justice	255	$32,715,574	$27,678,009	$5,037,565	15.40%
Department of State	7,747	$385,240,840	$342,732,342	$42,508,498	11.00%
Department of the Treasury	570	$11,704,722	$9,552,478	$2,152,243	18.40%
Department of Transportation	52	$2,802,799	$2,584,612	$218,188	7.80%
Department of Veteran Affairs	192	$4,377,255	$4,108,847	$268,408	6.10%
Environment Protection Agency	631	$9,389,259	$8,643,728	$745,532	7.90%
General Services Administration	111	$8,122,875	$6,057,461	$2,065,414	25.40%
Independent Agencies/Government Corporations	227	$16,360,791	$15,049,029	$1,311,761	8.00%
Other Civilian Agencies	111	$5,669,301	$5,301,894	$367,407	6.50%
Social Security Administration	176	$4,807,512	$3,987,276	$820,235	17.10%
USAAVE Auctions (FY2000 - FY2007)					
CECOM	**188**	**$153,865,877**	**$105,214,195**	**$48,651,682**	**31.62%**

Of equal interest to the volume of transactions and projected cost savings is the type of commodities and services purchased using e-RAs. For the most part, e-RAs involved relatively standard commercial products and services, in which vendor selection is primarily price-driven. Commercial products include computer software and hardware, office supplies, field warfare supplies (tents, batteries, flashlights, flak vests), trailers, refrigerators, dishwashers, and plasma televisions. Commercial services include hotel room and conferencing services, copier maintenance, training and services related to commodity purchases (installation services). For a complete list of commodities and services, see Appendix A and B, reproduced here from Brown and Ray (2007). As discussed above, standard commercial products and services are not the traditional product domain for reverse auctions. Reverse auctions traditionally target products with one buyer and several sellers; DoD is only one of many buyers for most of these commercial products and services, albeit a large buyer in at least some cases.

In addition to the cost savings estimates summarized above, e-RAs have been credited with several additional benefits—both price and efficiency related. In particular, e-RA cost-related benefits focus on improving transparency by increasing price visibility, providing a comprehensive audit trail (including the names and number of bidders, prices of their bids, the number of vendors contacted, and the number of vendors choosing not to bid), encouraging full and open competition and ensuring that prices are fair and reasonable. Efficiency-related benefits involve time savings both for the government contracting officials and from reducing the procurement cycle-time required to go from solicitation to contractor selection.

C. Reverse Auctions as a Market Research Pricing Tool

In traditional procurement processes throughout the federal government, procurement offices follow *FAR* 7.102 guidelines requiring them to compete procurements to the maximum extent practicable. This typically requires soliciting, but not necessarily obtaining, quotes from three to five vendors. Time is generally the limiting factor because buyers have to manually gather a list of qualified vendors, call or e-mail those vendors to request quotes and then assimilate the results of the submitted quotes into a report before selecting the winner. The small number of quotes obtained reflects the heavy workload and time needed to acquire and process the quotes.

In the 2006 Hearing on Federal Contracting in Disaster Preparedness and Response House Committee on Government Reform, FedBid testified that it provides "direct access to over 400,000 sellers in the government's seller database [the Central Contractor Registration]" (Fox, 2006, p. 6). FedBid adds up to 100 vendor sales agents each day during peak buying cycles, so the number of vendors contacted by a single buyer is quite large (FedBid, interview with W. Brown and L. Ray, September 19, 2007). Once a solicitation is posted with FedBid, it contacts the relevant vendors in its data base. As a result, e-RAs can involve significantly more competitors than traditional procurement processes.

Table 3 summarizes the average number of sellers that FedBid contacted per solicitation, the average number of sellers bidding per solicitation, and the average number of “no bids” per solicitation. All three measures offer different competition metrics; in general, potential competition and contestability of markets is the critical dimension. The average number of sellers bidding per solicitation is the most narrowly focused measure of competition. These sellers are clearly active competitors. The average number of sellers contacted is the broadest measure of competition; all of these sellers are potential competitors but their interest ranges from strong to none. The number of vendors who decided not to compete in that specific auction and responded with “no bid” provides an intermediate measure that reflects the number of sellers expressing interest in competing for the solicitation. For comparison, Appendix B reports the number of vendors participating in the USAAVE auctions; on average, there were 5.09 vendors per solicitation in the 188 procurement actions.

Table 3 and the USAAVE data in Appendix B highlight the advantages offered by e-RAs as they are currently implemented. In targeting commercial price-driven products and services, e-RAs are replacing traditional market research and expanding competition by tapping into a much larger pool of potential competitors. Increasing competition has two reinforcing effects. If prices are distributed probabilistically across potential suppliers, increasing competition gives DoD more draws from the distribution, increasing DoD’s chances of finding a lower-cost supplier. In addition, potential suppliers will likely submit prices that are closer to their actual costs as competition increases, accepting lower profits to increase their probability of winning the contract.

Table 3. FedBid Results
(Reproduced from Brown and Ray, 2007)

Government Agency	Number of Awards	Ave. No. of Sellers Bidding	Ave. No. of Bids per Auction	Ave. No. of "No bids" per Auction	Ave. No. of Sellers Notified	Ave. Savings in Dollars
FEDERAL GOVERNMENT	**18,401**	**5.9**	**13.6**	**44.6**	**836.5**	**$8,178.44**
DEPARTMENT OF DEFENSE	**5,932**	**4.7**	**10.2**	**55.7**	**1,012.9**	**$5,181.24**
Department of the Army	3,101	4.1	8.9	59.6	1048.2	$4,361.21
Department of the Air Force	316	3.7	8.7	58.8	1027.7	$14,695.88
Department of the Navy	1,710	5.7	11.9	48.3	971.5	$3,696.98
Other DoD Agencies	805	4.8	12.1	55	958.8	$7,758.06
CIVILIAN AGENCIES	**12,166**	**6.5**	**15.3**	**39.0**	**738.9**	**$9,792.04**
Department of Commerce	612	6.8	18.6	41	744.3	$7,675.68
Department of Homeland Security	1,251	5.9	14	35.5	628.2	$39,002.51
Department of Human Health Services	213	3.9	8.3	63.9	1079.6	$47,450.27
Department of Interior	18	8.8	21.2	42.3	728.5	$2,116.61
Department of Justice	255	5.4	12.8	53.2	1078.2	$19,755.16
Department of State	7,747	6.4	14.8	38.1	734.5	$5,487.09
Department of the Treasury	570	7.2	19.9	22.1	440.5	$3,775.86
Department of Transportation	52	14	36.3	54.7	995.2	$4,195.92
Department of Veteran Affairs	192	5.2	11.2	44.7	832.9	$1,397.96
Environment Protection Agency	631	8.5	17.7	36.7	721.8	$1,181.51
General Services Administration	111	6.8	15.4	17.6	269.2	$18,607.33
Independent Agencies / Government Corporations	227	6.7	14.8	100	1949.2	$5,778.68
Other Civilian Agencies	111	6.3	16.1	12.6	179.8	$3,309.97
Social Security Administration	176	6.6	18.5	44.8	737.3	$4,660.43

For example, suppose DoD is purchasing an item that has a price variability between \$100 and \$500. In particular, prices for potential suppliers are independently and uniformly randomly distributed between \$100 and \$500. As the number of suppliers contacted increases, the expected cost for the low-cost contractor decreases. The expected cost for the low-cost supplier is \$233.33 with two suppliers. This falls to \$200 with three suppliers, \$150 with seven suppliers, \$125 with 15 suppliers and \$120 with 19 suppliers. This is pictured by the lower line in Figure 2 below.

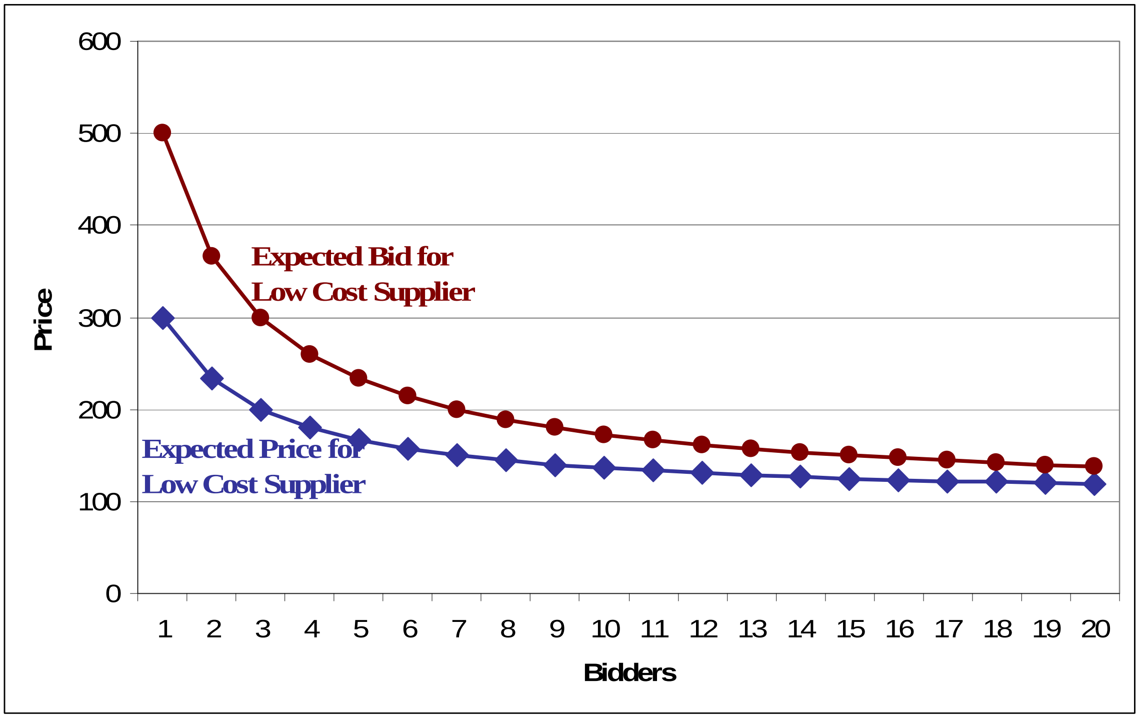

Figure 2. Effect of Competition on Expected First-Price Auction Price

However, the supplier will not reveal this price in their cost estimate. Instead, as described above, suppliers will overstate their costs to increase their profits, but the degree to which they can overstate costs will be tempered by the level of competition present. As competition increases, cost estimates will approach the supplier's actual cost because the contractor does not want to risk losing the contract. Figure 2 shows the expected profit maximizing bid for the low cost supplier as the number of competing suppliers increases. This is the expected price bid in a first-price sealed-bid auction or other similar contractor selection process. If there are two suppliers, the bid that maximizes expected profits for the low-cost supplier is $366.67 (recall cost is $233.33). This falls to $300 for three suppliers (cost $200), $200 for seven contractors (cost $150), $150 for 15 contractors (cost $125), and $140 for 19 contractors (cost $120).

This example in Figure 2 illustrates the dual impact of increasing competition as e-RAs have replaced more traditional market research. Suppose the number of competing suppliers increases from three to seven in the situation described above. With three contractors, the government would pay a price of $300 ($200 cost and $100 supplier surplus). As competition increases to seven suppliers, the expected government price falls to $200; the expected low-cost estimate falls from $200 to $150 as DoD receives quotes from more contractors and the low-cost contractor's bid includes a smaller profit margin ($50 as opposed to $100 with three suppliers). The 33% decrease in price is evenly divided between lower actual cost and lower supplier surplus. With 15 suppliers as opposed to 3, the government's expected cost would fall from $300 to $150; expected cost would fall by $75 (from $200 to $125) and competition would reduce supplier surplus by $75, from $100 to $25.

Note that this figure also illustrates the revenue equivalence theorem. The upper line represents the expected cost for the second-lowest-cost supplier. If DoD used either an English or second-price sealed-bid auction, this would represent the price paid to the winning (low-cost) contractor. Under a first-price sealed-bid or Dutch auction, this line represents the expected profit maximizing bid for the low-cost contractor. Essentially, the low-cost contractor attempts to estimate cost for the second-lowest-cost contractor. This upper line represents the government's expected cost for all the standard auction mechanisms.

D. Lessons Learned From Using Federal Reverse Auctions

The theory describing reverse auctions characterizes them as an appropriate mechanism to address transactions when there is a single buyer and several sellers. In contrast, DoD and federal experience with reverse auctions seems to emphasize transactions in which there are many sellers but the government is only one of many potential buyers of the product or service, including relatively standard price-driven commercial commodities and services. In this use, DoD has substituted the reverse auction, and support from the auction provider, for the market research federal procurement agents conduct when DoD purchases these items through a more traditional procurement process.

The alleged cost-savings attributed to reverse auctions is calculated as the difference between the government's independent cost estimate and the final price after the auction. It is likely that these savings reflect an increase in competition from e-RAs. Competition has two effects: it increases the number of cost estimates, which increases the probability of finding a lower cost estimate; it decreases the sellers' surplus as competition encourages bids closer to actual costs. Data from FedBid and USAAVE indicate that reverse auction significantly increases the number of suppliers actually bidding on a contract, compared to the traditional market research process. Data from FedBid further emphasizes that potential competition might be significantly greater than this because a large number of suppliers are notified about the solicitation, though some choose to submit "no bid" and others are even less active.

Winners in reverse auctions can also be based on best value, as opposed to best price, where best value includes price, past performance and technical factors—depending on the needs and preferences of the buyer.[8] The buyer states whether the award will be based on the lowest price or the best-value in the solicitation. Depending on the size and complexity of the procurement, the buyer might also provide specific weights for evaluating price, technical factors, timeliness, and/or past performance. Currently, price, delivery time, and past performance are the most common factors used by the federal agencies.

USAAVE has the capability to support best-value auctions using a two-step sealed-bidding process; the sellers submit their technical proposal first with all other required information (such as company qualifications and past performance

[8] FAR 13.106-2(4)): For acquisitions conducted using[…] a method that permits electronic response to the solicitation, the contracting officer may—(i)[…] identify from all[…] offers received one that is suitable to the user, such as the lowest priced brand name product, and quickly screen all lower priced quotations or offers based on readily discernible value indicators, such as past performance, warranty conditions, and maintenance availability; or (ii) Where an evaluation is based only on price and past performance, make an award based on whether the lowest priced of the quotations or offers having the highest past performance rating possible represents the best value when compared to any lower priced quotation or offer.

information), so that the buyer can determine if that vendor is a qualified supplier. According to CECOM, “Once the evaluation was completed that these [vendors] are technically acceptable they would be put in a pool then be invited to go ahead and partake in the reverse auction” (Meinert, 2007). USAAVE also has a weighted value function that is particularly useful in determining a best-value award. Non-price factors are evaluated and assigned a subjective adjectival grade in accordance with a predetermined grading scale. After the adjectival rating is assigned to the factors in the vendor’s bid, an overall weighting scale is used to calculate a final bid score that is posted with the vendor’s bid. Both the buyer and the vendor who submitted the subject bid are able to see these weightings, which the agency believes helps to prevent protests (Meinert, 2007).

FedBid has a similar automated best-value weighting tool, but it is currently deactivated because its e-RAs are primarily used for competing price-driven commodities in a simplified acquisition scenario. Delivery schedule is the primary factor federal agencies consider when they want to include factors other than price. In this case, FedBid encourages vendors to submit multiple bids where the price may be lower for slower delivery times and higher for faster delivery times. The buyer then evaluates and selects the winning bidder by trading-off monetary and non-monetary factors as accounted for in the solicitation. The winning bidder may or may not be the “lowest” bidder at the conclusion of the auction, depending on the best-value determination. One complication is using the best-value approach if uncertainty exists in setting the appropriate weighting factors, which will be addressed in detail in the following section.

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IV. Procurement Auctions as a Market Research Tool: The I^2A^2 Mechanism

A. Introduction

Any decision a defense organization makes to procure a product or service from an external supplier is, in actuality, a series of interdependent decisions. In particular, the procurement decision involves, at a minimum, determining:

1. *What* should be procured;
2. *How* it should be procured;
3. *From whom* it should be procured; and
4. *At what price it should be procured.*

Economic analyses of the procurement process have, to this date, tended to focus on the latter three questions while neglecting the prerequisite first question: What (precisely) should be procured? Instead of offering insight into how this primary question might be addressed, however, economists have simply assumed the answer to be determined a priori: The procuring organization presumably knows what they want, the argument goes, so it is fair to assume that the description of what is to be procured can be relatively easily determined internally.

Procurement practitioners are well aware, however, that determining what should actually be procured can, contrary to the assumptions of most economists, be a complicated and arduous process. For example, Federal Acquisition Regulation (*FAR*) requires an information gathering phase that may involve conducting extensive market research, generating a reasonable cost estimate, identifying basic product requirements, as well as generating appropriate evaluation criteria and metrics (*FAR*

Parts 7, 10, & 11). These tasks require the attention and energies of multiple individuals within the organization from contracting officers to end-users.

Even if economists were to generally recognize that determining what should be procured is a complex process, it may nonetheless not be immediately apparent how the field of economics can contribute to our understanding of the issue. After all, why should not the analysis of this initial stage of the procurement problem simply be left to engineers, market researchers, and others? The reason, as we shall see, arises from the fact that determining precisely what should be procured requires procuring organizations to gather and aggregate a broad set of information that is:

1. *Incomplete*—No single actor or organization possesses all of the relevant information. The procuring organization may have some understanding of its needs but may possess only limited knowledge regarding the capabilities of current technology and probably even less knowledge about the costs incurred by individual contractors to produce this technology. Each individual contractor, on the other hand, may have a good understanding of its own cost structure and technological capabilities, but may possess only limited knowledge about the procuring organization's true needs or about the cost structures and technological capabilities of its competitors.

2. *Diffuse*—The relevant information for determining what should be procured is spread across numerous organizations. The full gamut of information about needs, costs, and capabilities is spread among the procuring organization and all of its potential contractors, which could be numerous. A key piece of information about state-of-the-art capabilities, for example, could be possessed by only a single contractor while another key piece of information could be exclusively possessed by a different contractor. Full information aggregation thus requires extracting knowledge from a wide number of organizations—a formidable undertaking for traditional market research methods.

3. *Private*—Information possessed by any organization, particularly about costs or capabilities, may be known only within that organization and, moreover, the organization may have little incentive to truthfully reveal its information. For example, while traditional market research might involve asking a contractor how the procuring organization's needs might best be satisfied by existing

> technology, the contractor has every incentive to convince the procuring organization that its needs can best be met by technologies in which that particular contractor has a comparative cost or capability advantage. Effective information aggregation requires the creation of incentives for contractors to truthfully reveal their private information.

While other fields of study have much to contribute to determining precisely what an organization should procure, the problem of overcoming the above three fundamental information “obstacles” to achieve effective information aggregation is one that is ideally suited for economics. In particular, the economic field of mechanism design is devoted to the development of appropriate systems which (a) create incentives for individuals and actors to truthfully reveal their private information, (b) efficiently aggregate this diverse (and sometimes conflicting) information, and (c) identify optimal choices based on the aggregated information.

In the analysis that follows, we will employ the economic methods of mechanism design to develop an iterated procurement auction mechanism which endogenously aggregates information and determines what should be procured, how it should be procured, from whom it should be procured, and at what price it should be procured. We will first introduce an economic model which captures a number of important details related to the incentives and information conditions which exist in the procurement arena. We will subsequently present the iterated auction mechanism and illustrate how it addresses all four key procurement questions identified above. Finally, we will employ computer simulation to evaluate the performance of the proposed auction mechanism relative to alternative procurement methods.

B. Quality and Buyer Incentives

Whether procuring a new aircraft, a desktop computer, or even lawn-care services, in addition to price considerations, there may be a wide number of quality dimensions over which to measure a product/service offering from a potential contractor. Answering the “what should we procure” question essentially boils down to determining which of all the possible quality dimensions should matter and how much they should matter.

For example, determining which type of aircraft to procure is equivalent to determining the relative importance of each of a myriad of possible quality dimensions, such as speed, maneuverability, range, and so on. In turn, the relative importance or “weight” that a procuring organization places on different quality dimensions will determine the types of aircraft offered by contractors and the specific type of aircraft that is ultimately acquired. The relative weight placed on each quality dimension also indirectly determines which contractor will ultimately produce the aircraft, with the winning contractor generally being the one capable of providing the greatest “bang for the buck”—“bang” being specifically measured by the weights placed on the various dimensions of quality.

While there will typically be many different dimensions of quality over which to evaluate a product or service, in what follows we will simplify our presentation by limiting the analysis to two dimensions. Thus, suppose that the array of quality elements is limited to two components: reliability (x) and delivery schedule (y). Note that the analysis that follows can be generalized to a scenario with any number of quality elements, but it will simplify the discussion to focus on the two-dimensional case.

The relative importance of these two quality dimensions to the buyer (i.e., the procuring organization) can be expressed by weights placed on the two elements when determining overall quality. In particular, let overall quality be given by $\alpha x + \beta y$, where α indicates the importance or weight placed on reliability (x) while β is the importance or weight placed on delivery schedule (y). A tradeoff between the two elements of quality is induced by making the additional assumption that $\alpha + \beta = 100$. Thus, if α is relatively high (i.e., reliability is relatively important) then β must be relatively low (i.e., delivery schedule is relatively less important) and vice versa.

Suppose the buyer procures a product or service with reliability level x and delivery schedule y from a chosen contractor, and the buyer pays the contractor a price P for this product or service. Then, the overall value (v) to the buyer is determined by subtracting price (P) from quality (αx + βy). In other words, we have:

v = overall value
x, y = elements of quality
α, β = weight placed on each element of quality, where $\alpha \in$ U[0,100] and β=100-α
P = price
$$v = \alpha x + \beta y - P$$

C. Cost and Seller Incentives

Each contractor or potential seller has a cost function that is independent of the buyer's value function. In particular, we assume that any given contractor *j* who provides a product or service with quality levels x and y has a cost function that can be expressed as:

C_j = total cost from firm *j*
x, y = elements of quality
a_j, b_j = marginal cost parameters for each element of quality, where $a_j, b_j \in$ U[0,10]
$$C_j = a_j x^2 + b_j y^2$$

Note that the firm's cost function is quadratic in order to capture the usual condition of increasing marginal costs. In other words, if the firm increases quality in one dimension, costs go up exponentially rather than at a constant rate. Also note that the cost function creates a tradeoff between quality elements: For any given level of total cost, any increase in quality element x will necessitate a decrease in quality element y and also vice versa.

Contractor profits are, of course, simply price minus cost. Thus, any given contractor *j* which sells a product or service with quality levels x and y at a price P has a profit given by:

$$\Pi_j = \text{total profit for contractor } j$$

$$\Pi_j = P - C_j$$

$$\Pi_j = P - a_j x^2 - b_j y^2$$

D. Buyer and Seller Information

As noted previously, it is often the case that the buyer in any procurement (the DoD in this case) has only imperfect information about its own preferences. In other words, the buyer is not always fully aware of all possible capabilities of available technology nor is the buyer fully aware of the precise benefits of these capabilities. Similarly, contractors may have better (or at least different) information about the capabilities of available technology, but may have only an imprecise understanding of the benefits of these capabilities for the buyer. Thus, information about the true nature of buyer value is both incomplete and diffuse, as described previously.

In the model we have presented, the uncertainty about buyer value can be captured by assuming that both the buyer (DoD) and the sellers (contractors) have incomplete information about the true value of α and β (the weights on the different elements of quality) in the buyer's value function.

To represent this incomplete information condition, we can envision the information about α and β that is held by the buyer and each seller as being provided via a series of independent draws by each player from an opaque urn containing 100 balls. In this urn, there are α black balls and β white balls (recall that $\alpha + \beta = 100$). An individual player (be it a buyer or seller) infers the true number of black and white balls in the urn (the true values of α and β) from the information received from its draws (the number of black and white balls).

To represent the different levels of precision in information about buyer preferences, suppose that the buyer (DoD) draws m_b balls from the urn while each seller (contractor) draws m_s balls from the urn. Note that the buyer might have more precise information than each contractor, in which case we would have $m_b > m_s$, or the buyer might have less precise information than each contractor, in which case we would have $m_b < m_s$.

Recognize that if the buyer draws B black balls and W white balls from the urn, then his ex ante estimates of the values of α and β will be given by:

$$\alpha_b = \text{buyer's ex ante estimate of the value of } \alpha$$
$$\beta_b = \text{buyer's ex ante estimate of the value of } \beta$$
$$\alpha_b = \frac{B}{B+W} \times 100 = \frac{B}{m_b} \times 100$$
$$\beta_b = \frac{W}{B+W} \times 100 = \frac{W}{m_b} \times 100$$

Each individual contractor j's ex ante estimate of the value of α and β (α_j and β_j) will be determined the same way based on the individual contractor's draws from the urn.

Note that each player's information about the true value of α and β (i.e., the number of black and white balls drawn by that player) is private information, known only to that player. This means that the buyer or any contractor may or may not truthfully reveal his or her information about α and β in the process of any procurement mechanism.

Also assumed to be private information are the marginal cost parameters a_j and b_j associated with any contractor j's cost function. In other words, a contractor's true cost structure is known (ex ante) only to that contractor.

Before proceeding, it is important to note an important incentive effect of the presence of private information about both cost and value in this model: Unless somehow induced to truthfully reveal its private information, any contractor j will generally seek to convince the buyer that its estimate α_j is high (and, thus, its estimate β_j is low) whenever its marginal cost parameter a_j is low relative to its cost parameter b_j, and will generally seek to convince the buyer that its estimate α_j is high (and, thus, its estimate β_j is low) whenever its marginal cost parameter a_j is low relative to its cost parameter b_j. In other words, each contractor has an incentive (ex ante) to deceive the buyer in a way that steers the buyer towards quality weights, which correspond with the contractor's own relative cost advantage and thus increases its likelihood of winning the contract.

E. The Iterated Information Aggregation Auction (I^2A^2)

The discussion to this point has simply introduced a model of the procurement environment and, thus, has been applicable to any type of procurement mechanism. In this section, we will describe our proposed iterated information aggregation auction mechanism (hereafter, I^2A^2 mechanism) and calculate the outcome of this mechanism when used in the procurement environment that we have been describing.

The I^2A^2 mechanism consists of six stages, as illustrated in Figure 3 below. The stages shaded black represent actions by the sellers, the stages shaded white represent actions by the buyer or auctioneer, and the stage shaded gray represents the starting probabilistic action by "nature" in which all players are endowed with their initial information.

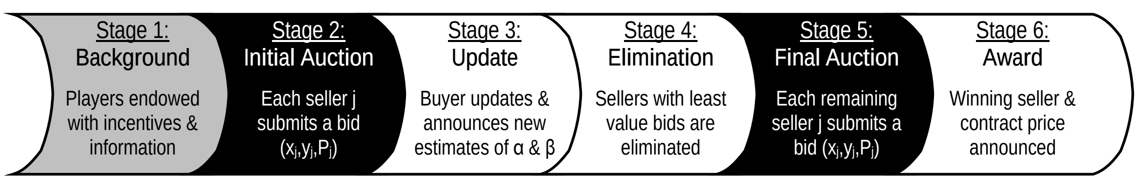

Figure 3. The Iterated Information Aggregation Auction (I^2A^2) Mechanism

1. Stage 1: Background

Stage one is not actually part of the auction mechanism itself; however, it is included in our description here because it represents the background setting of the initial incentives and information that players possess as they participate in the I^2A^2 mechanism.

As part of this stage (and prior to the actual auction), the buyer will be endowed with incentives in the form of values for the quality parameters α and β as well as estimates $\hat{\alpha}$ and $\hat{\beta}$ of these parameter values. The buyer will not know the true value of α and β and will begin with only the estimates $\hat{\alpha}$ and $\hat{\beta}$. Recall that these estimates are modeled as being based on m_b independent draws from an urn containing α black balls and β white balls.

In this pre-auction stage, each seller will similarly be endowed with its initial incentive and information condition. In particular, any seller j will be endowed with incentives in the form of values for the cost parameters a_j and b_j, which are known to the seller (and only that seller), as well as estimates α_j and β_j of the true values of the quality parameters α and β. Recall that seller estimates of α and β are modeled as being based on m_s independent draws from an urn containing α black balls and β white balls.

2. Stage 2: Initial Auction

In stage two of the game, each contractor j will submit a bid to the buyer (DoD) that consists of two quality elements (x_j and y_j) and a price (P_j). The objective each contractor has in stage two is to decide the optimal levels of P, x, and y based on the individual contractor cost function and the information about buyer preferences from the draw in stage one.

An individual seller j has two crucial components of information. First, the contractor has complete knowledge of its individual cost function:

$$C_j = a_j x_j^2 + b_j y_j^2$$

The contractor also has some information (as much as, but different from, any other individual contractor) about the true values of α and β.

i. The Generalized Second-Price Auction and Truthful Revelation of Costs

Both the initial and final auction stages will be conducted as a generalized multi-dimensional second-price auction. This means that the bids will first be ranked according to the overall value delivered (as perceived by the buyer), with the value of any contractor j's bid being given by:

$$v_j = \hat{\alpha} x_j + \hat{\beta} y_j - P_j$$

The sellers from the initial auction who are chosen to proceed to the final auction will be those sellers who submit the n highest value bids. The winner in the final auction will be the seller who submits the highest value bid. The feature that makes the auction a generalized second-price auction is that the winning seller in the final auction is not paid the price it bid but rather the highest price the seller *could have* bid and still been the winner in the final auction.

For example, suppose seller j submits a bid (x_j,y_j,P_j) that generates perceived buyer value v_j and that seller i submits a bid (x_i,y_i,P_i) that generates perceived buyer value v_i. Further suppose that seller j's bid is the highest value bid and that the seller i's bid is the second-highest value bid. In this case, seller j would win the auction and would deliver a product/service with quality dimensions x_j and y_j, and in return, the buyer would pay seller j a price of $P_j + (v_j - v_i)$. In other words, the winning seller is paid the price bid plus the additional value delivered over the second-place bidder. Note that the winning seller is consequently always paid as much or more than the price bid.

This generalized second-price auction format is employed because it induces truthful revelation of costs. This well-known characteristic of generalized second-price auctions will not be proven here, but the implications in the current context are that it is the optimal strategy for any seller j to submit, as part of its bid, a price P_j that is exactly equal to its cost C_j of delivering a product/service with the quality values x_j and y_j submitted in its bid. Thus, each contractor j will bid such that:

$$P_j = C_j = a_j x_j^2 + b_j y_j^2$$

While the winning seller will not be announced until after the final auction, it is important to note that bids placed in the initial auction are also considered binding bids. In other words, if it is determined in the last stage of the I^2A^2 mechanism that a bid placed in the initial auction actually delivers higher overall value to the buyer than any bid placed in the final auction, then the buyer can (and will) choose as the ultimate winning bid the highest-value bid that was placed in the initial auction. Allowing for a bid placed in the initial auction to be selected as the ultimate winning bid guarantees that bids placed in the initial auction are also truth-revealing (such that any contractor j will bid $P_j = C_j$ in the initial auction as well). Note that, if bids in the initial auction were not binding, a seller would have an incentive to bid a price that was below cost to increase its chances of being identified as a high-value bidder and be selected to participate in the final auction. With binding initial bids, it is instead optimal for each contractor to bid truthfully (setting price equal to cost).

An additional important characteristic of the generalized second-price auction is that such an auction can generally be expected to produce contract prices that are (in expectation) the same as the contract prices that would be generated in a more traditional first-price auction (in which the winning seller is paid the exact price it bid). Again, this result will not be proven here, but the Revenue Equivalence Theorem discussed earlier states that the second-price procurement auction will result in the same contract costs on average as a first-price procurement auction, assuming that the bidders are risk-neutral and that certain other general conditions hold. In fact, the entire analysis which follows can be easily adapted to a mechanism in which first-price auctions are employed; however, the analysis would be a bit more complex (the price a contractor bids would no longer precisely equal its cost; however, the buyer could calculate the seller's optimal pricing strategy and then backward-induce its true cost from the price bid).

ii. Eliminating Low-Value Bidders and Truthful Maximization of Value

As we have noted briefly to this point and as will be addressed in more detail, those sellers whose bids in the initial auction generate the lowest overall value for the buyer will be eliminated from the process, meaning they will not be invited to submit bids in the final auction. This is an important feature of the mechanism because it ensures that it is in each contractor's best interest to submit an overall bid that, given the contractor's information, maximizes the value it can profitably provide the buyer.

To understand why contractor elimination is an important feature of the mechanism, imagine what would happen if all contractors who bid in the initial auction were also invited to bid in the final auction. As we will see, the I^2A^2 mechanism is designed such that the buyer uses contractor bids placed in the initial auction to update its estimate of the importance of various dimensions of quality (i.e., to update its estimates of α and β) before proceeding with the final auction. If all contractors who bid in the initial auction also bid in the final auction, a contractor would have little incentive to offer a bid in the initial auction that maximized buyer value, but would instead have every incentive to offer a bid that might simply steer the buyer towards quality weights that correspond with the contractor's own relative cost advantage, thereby increasing the likelihood of winning the contract in the final auction. For example, if a seller j had a very low value for a_j (a low marginal cost of providing quality dimension x), it might offer a very high x_j in its initial bid in hopes of convincing the buyer that quality dimension x was more important than it really was. This would severely undermine the most distinctive feature of the I^2A^2 mechanism, which is truthful information revelation and aggregation.

However, with the provision that only the n highest-value bidders will be able to offer bids in the final auction, the I^2A^2 mechanism creates competition at the initial auction stage. These competitive pressures create a strong incentive for each seller to submit a bid in the initial auction that truthfully maximizes the value it can profitably provide the buyer.

iii. The Contractors' Optimal Bidding Strategy

As we have shown, the use of the generalized second-price auction will induce each contractor to bid in a manner that truthfully reveals its cost (i.e. to bid P_j=C_j) and eliminating the least-value bidders after the initial auction will induce each contractor to bid in a manner that truthfully maximizes buyer value. Combining these two results allows us to calculate each contractor's optimal bidding strategy.

In particular, contractor j's objective in the initial auction is to submit a bid with $P_j = C_j$ and also:

$$\begin{aligned}
&\text{Choose } x_j \text{ and } y_j \text{ to maximize buyer value} \\
&\Rightarrow \text{Choose } x_j \text{ and } y_j \text{ to maximize } \alpha_j x_j + \beta_j y_j - P_j \\
&\Rightarrow \text{Choose } x_j \text{ and } y_j \text{ to maximize } \alpha_j x_j + \beta_j y_j - C_j \\
&\Rightarrow \text{Choose } x_j \text{ and } y_j \text{ to maximize } \alpha_j x_j + \beta_j y_j - \left(a_j x_j^2 + b_j y_j^2\right) \\
&\Rightarrow \text{Choose } x_j \text{ and } y_j \text{ to maximize } \left(\alpha_j x_j - a_j x_j^2\right) + \left(\beta_j y_j - b_j y_j^2\right)
\end{aligned}$$

Given that there is no interaction between x_j and y_j in the above objective function, we can separate the objective into two independent objectives:

$$\begin{gathered}
\text{Choose } x_j \text{ to maximize } \alpha_j x_j - a_j x_j^2 \\
\text{and} \\
\text{Choose } y_j \text{ to maximize } \beta_j y_j - b_j y_j^2
\end{gathered}$$

Each contractor j's optimal bid can then be determined by differentiating each of the above objective functions (and setting the derivative equal to zero) to find the maximum value attainable for each function.

$$\frac{d}{dx_j}\left(\alpha_j x_j - a_j x_j^2\right) = \alpha_j - 2a_j x_j = 0$$

$$\Rightarrow x_j = \frac{\alpha_j}{2a_j}$$

and

$$\frac{d}{dy_j}\left(\beta_j y_j - b_j y_j^2\right) = \beta_j - 2b_j y_j = 0$$

$$\Rightarrow y_j = \frac{\beta_j}{2b_j}$$

Thus, it is each contractor's optimal strategy in the initial auction to submit a bid (x_j,y_j,P_j,) such that:

$$x_j = \frac{\alpha_j}{2a_j}$$

$$y_j = \frac{\beta_j}{2b_j}$$

$$P_j = a_j x_j^2 + b_j y_j^2$$

3. Stage 3: Update

In stage three of the I^2A^2 mechanism, the buyer updates its own estimates of the true values of α and β based on the bids submitted by contractors in the initial auction (stage 2). The sellers do not take any action in this stage.

At this point in the process, the buyer has two components of information from which to estimate the true values of α and β. First, the buyer knows its individual estimates from the background stage one (α_b and β_b). Additionally, the buyer also knows the bids (x_j, y_j, P_j) from each contractor in the initial auction of stage two.

Although the individual contractors have not directly revealed their estimates of α and β, the buyer can infer each contractor j's estimates α_j and β_j based on its bid (x_j, y_j,

P_j) in the initial auction. From our analysis above, we know that optimization by contractor j yields a bid with:

$$x_j = \frac{\alpha_j}{2a_j} \Rightarrow a_j = \frac{\alpha_j}{2x_j}$$
$$y_j = \frac{\beta_j}{2b_j} \Rightarrow b_j = \frac{\beta_j}{2y_j}$$
$$P_j = a_j x_j^2 + b_j y_j^2$$

Substituting the first two equations above into the third yields:

$$P_j = \left(\frac{\alpha_j}{2x_j}\right)x_j^2 + \left(\frac{\beta_j}{2y_j}\right)y_j^2$$
$$P_j = \frac{\alpha_j x_j}{2} + \frac{\beta_j y_j}{2}$$
$$2P_j = \alpha_j x_j + \beta_j y_j$$

Finally, substituting $\beta_j = 100-\alpha_j$ into this last equation gives us:

$$2P_j = \alpha_j x_j + \left(100-\alpha_j\right)y_j$$
$$2P_j = 100y_j + \alpha_j\left(x_j - y_j\right)$$
$$2P_j - 100y_j = \alpha_j\left(x_j - y_j\right)$$
$$\alpha_j = \frac{2P_j - 100y_j}{x_j - y_j}$$
$$\beta_j = 100 - \alpha_j = \frac{100\left(x_j - y_j\right) - 2P_j + 100y_j}{x_j - y_j} = \frac{2P_j - 100x_j}{x_j - y_j}$$

Thus, the buyer can infer any contractor j's estimates of α_j and β_j from its bid (x_j, y_j, P_j). Combining these estimates with the buyer's own estimates α_b and β_b allows the buyer to generate updated estimates of α and β as follows:

$\hat{\alpha}$ = updated estimate of α

$\hat{\beta}$ = updated estimate of β

N = number of sellers bidding in initial auction

$$\hat{\alpha} = \frac{m_b \alpha_b + m_s \sum_{j=1}^{N} \alpha_j}{m_b + N m_s}$$

$$\hat{\beta} = \frac{m_b \beta_b + m_s \sum_{j=1}^{N} \beta_j}{m_b + N m_s}$$

After the buyer updates its estimates of α and β, the buyer provides an "update" to the sellers by announcing the new estimated values $\hat{\alpha}$ and $\hat{\beta}$ as calculated above. This announcement effectively puts all players (the buyer and all sellers) on equal footing in terms of information about the true values of α and β. The buyer has effectively aggregated all the diffuse private information about α and β that exists in the market and shared this aggregation with all the sellers. Note the number of initial sellers is a key variable in the I^2A^2 mechanism because the larger the pool of information, the more accurate the estimates $\hat{\alpha}$ and $\hat{\beta}$ will be in this stage.

4. Stage 4: Elimination

In the fourth stage of the I^2A^2 mechanism, the buyer will rank the sellers according to the estimated value delivered by their bids in the initial auction. In particular, the buyer will use the new parameter estimates $\hat{\alpha}$ and $\hat{\beta}$ calculated in stage three to assign an overall value to each contractor's bid. The estimated value to the buyer from any contractor j's bid consisting of quality levels xj and yj with price Pj will thus be:

$$v_j = \hat{\alpha} x_j + \hat{\beta} y_j - P_j$$

Assigning a value to each contractor's bid according to this formula, the contractors will be ranked from highest value to lowest value. Only a subset of contractors, those whose initial bids generated the greatest value, will be allowed to continue to the final auction in the following stage. As noted previously, eliminating sellers prior to the final auction is necessary to create competition in the initial auction stage and induce each seller to submit an initial bid that truthfully maximizes (to the best of the seller's perception at that point) the value that it can profitably provide the buyer.

5. Stage 5: Final Auction

In stage five of the I^2A^2 mechanism, each seller who was retained from the previous stage submits a new bid in a second and final auction. The bidders in this final auction will incorporate the new aggregate estimates of α and β, which were calculated and announced by the buyer in stage three. It will again be optimal for each seller to truthfully reveal cost as part of its bid (i.e., to bid a price equal to cost) and to bid in a manner that truthfully maximizes buyer value.

Thus, the objective of any contractor j in the final auction is to submit a bid with $P_j = C_j$ and to also:

$$\begin{aligned}
&\text{Choose } x_j \text{ and } y_j \text{ to maximize buyer value} \\
&\Rightarrow \text{Choose } x_j \text{ and } y_j \text{ to maximize } \hat{\alpha}x_j + \hat{\beta}y_j - P_j \\
&\Rightarrow \text{Choose } x_j \text{ and } y_j \text{ to maximize } \hat{\alpha}x_j + \hat{\beta}y_j - C_j \\
&\Rightarrow \text{Choose } x_j \text{ and } y_j \text{ to maximize } \hat{\alpha}x_j + \hat{\beta}y_j - \left(a_j x_j^2 + b_j y_j^2\right) \\
&\Rightarrow \text{Choose } x_j \text{ and } y_j \text{ to maximize } \left(\hat{\alpha}x_j - a_j x_j^2\right) + \left(\hat{\beta}y_j - b_j y_j^2\right)
\end{aligned}$$

This maximization problem is solved in the same manner as was illustrated above for the initial auction in stage two. In a result that parallels the result from the initial auction, we find that it is any contractor j's optimal strategy to submit a bid (x_j,y_j,P_j,) in the final auction such that:

$$x_j = \frac{\hat{\alpha}}{2a_j}$$

$$y_j = \frac{\hat{\beta}}{2b_j}$$

$$P_j = a_j x_j^2 + b_j y_j^2$$

Note that all sellers have the same information about the buyer's quality parameters α and β in the final auction, thus the only thing that will distinguish the sellers' final bids will be their differing cost parameters a_j and b_j.

6. Stage Six: Award

The last stage of the I^2A^2 mechanism is the award announcement. The successful seller is the firm whose bid maximizes total value as perceived by the buyer (i.e., the one whose bid maximizes $\hat{\alpha}x_j + \hat{\beta}y_j - P_j$). As noted previously, however, the auction is conducted as a generalized second-price auction; therefore, the winning firm is not paid its own price bid. Instead, the winning firm is paid the highest price that it could have bid and still won the auction.

Recall from above that using a generalized second-price auction induces the contractors to reveal their true costs and that the Revenue Equivalence Theorem implies that the buyer would pay the same price (on average) regardless of whether a first-price or second-price auction is used.

The preceding analysis has allowed us to full characterize the expected behavior and outcomes under the I^2A^2 mechanism. To evaluate the performance of this mechanism, however, we must compare it to more traditional procurement mechanisms, which are introduced in the next section

F. The Alternative: Single Procurement Auctions

To identify and quantify the benefits of using the I^2A^2 mechanism, we must compare it to the more traditional single procurement auction alternative. In what follows, we will present four possible variations of the single procurement auction and characterize the expected behavior and outcomes under each variation. Each of the four variations follows a similar structure as illustrated in Figure 4 below.

Figure 4. Single Procurement Auction Structure

Figure 4 highlights that the background stage (Stage 1) as described for the I^2A^2 mechanism also exists in each of the single-auction variations. In other words, prior to the actual auction, the buyer will be endowed with incentives in the form of values for the quality parameters α and β as well as estimates $\hat{\alpha}$ and $\hat{\beta}$ of these parameter values. Moreover, each seller j will be endowed with incentives in the form of values for the cost parameters a_j and b_j as well as estimates α_j and β_j of the true values of the quality parameters α and β.

It is also important to observe from Figure 2 that stage two ("publish") and stage four ("update") are considered optional. It is the optional nature of these two stages that will separate our four variations of the single procurement auction. The "publish" stage involves the buyer communicating α_b and β_b—its own starting estimates of α and β—to the sellers before the auction. The buyer will publish its prior estimates in two of the variations below and the buyer will not in the two other variations. The "update" stage involves the buyer updating its estimates of α and β based on the bids submitted by the contractors. The buyer will perform an update in two of the variations below and the buyer will not in the two other variations.

In each of the variations that follow, we will continue to assume that a generalized-second price auction is employed. This not only assures that we are comparing "apples to apples" when comparing alternatives but also greatly simplifies the analysis since the generalized second-price auction will induce each contractor to bid in a manner that truthfully reveals its cost (i.e. to bid $P_j=C_j$). Recall that the winning bid and the price paid (on average) will be the same for a second-price auction as for the first-price auction and, moreover, the entire analysis which follows can be easily adapted to variations employing first-price auctions; however, the analysis would be a bit more complex.

1. Variation #1: No Publish / No Update

The simplest variation of the single procurement auction is one in which the buyer neither publishes its own prior estimates of the weights on the various dimensions of quality nor does it update its estimates of those weights after observing the bids submitted.

By not updating its estimates of α and β based on seller bids, the buyer is essentially relying exclusively on its own prior information about what type of product/service will deliver the most value and ignoring any information that the sellers might possess. Moreover, the final award will be determined according to the buyer's own prior estimates of α and β.

By not publishing the weights in advance of the auction, the buyer is essentially choosing to not reveal precisely how the auction winner will be determined. Each seller must instead rely only on its own individual prior estimates of α and β when formulating a bid.

This variation of the single auction approximates a situation in which the buyer is ambiguous about the evaluation criteria during the solicitation (perhaps to mitigate protest risk), but the buyer is fairly certain about the appropriate evaluation criteria and its ultimate desired product/service.

Recognize that the seller's optimization problem in this variation of the single auction is the same as for the initial auction in the I^2A^2 mechanism. Thus, any seller j's optimal bid (x_j,y_j,P_j) will again be given by:

$$x_j = \frac{\alpha_j}{2a_j}$$
$$y_j = \frac{\beta_j}{2b_j}$$
$$P_j = a_j x_j^2 + b_j y_j^2$$

Since the buyer does not update its estimates of α and β in this variation, the winning seller will be the one whose bid maximizes the buyer's perceived overall value according to its prior estimates α_b and β_b. Thus, the buyer will assign any bid (x_j,y_j,P_j) a value $v_j = \alpha_b x_j + \beta_b y_j - P_j$ and the winning bid will be the one which maximizes this value.

2. Variation #2: No Publish / Update

A second variation of the single procurement auction is one in which the buyer does not publish its own prior estimates of the weights α and β, but does update its estimate of those weights after observing the bids submitted. This variation of the single auction approximates a situation in which the buyer waits until the bids are submitted to determine its evaluation criteria (i.e., the final weights it will place on each dimension of quality) and chooses not to communicate its own prior estimate of those weights before the auction—perhaps because the prior estimates might differ significantly from the final weights used to evaluate bids.

As with the previous variation (and with the initial auction in the I^2A^2 mechanism), the seller must rely only on its own individual prior estimates of α and β when formulating a bid. Consequently, any seller j's optimal bid (x_j,y_j,P_j) will again be given by:

$$x_j = \frac{\alpha_j}{2a_j}$$

$$y_j = \frac{\beta_j}{2b_j}$$

$$P_j = a_j x_j^2 + b_j y_j^2$$

As in the I^2A^2 mechanism, the buyer in this variation of the single auction will update its estimates of α and β before assigning a value to each submitted bid. In fact, because the seller's optimal bid in this single-auction variation is the same as its optimal bid in the initial auction from the I^2A^2 mechanism, the buyer's calculation of updated estimates of α and β are also the same:

$$\hat{\alpha} = \text{estimate of optimal } \alpha$$

$$\hat{\beta} = \text{estimate of optimal } \beta$$

$$\hat{\alpha} = \frac{m_b \alpha_b + m_s \sum_{j=1}^{N} \alpha_j}{m_b + N m_s}$$

$$\hat{\beta} = \frac{m_b \beta_b + m_s \sum_{j=1}^{N} \beta_j}{m_b + N m_s}$$

In this variation, the winning seller's initial bid maximizes the buyer's perceived overall value according to these updated estimates of α and β. Thus, the buyer will assign any bid (x_j,y_j,P_j) a value , $v_j = \hat{\alpha} x_j + \hat{\beta} y_j - P_j$ and the winning bid will be the one that maximizes this value.

3. Variation #3: Publish / No Update

The third variation of the single procurement auction is one in which the buyer <u>does</u> publish its own prior estimates of the weights α and β, but does <u>not</u> update its estimate of those weights after observing the bids submitted. In other words, in this variation the buyer ultimately evaluates bids using only its own prior information about product/service quality (i.e., its own prior estimates of α and β) but informs the sellers upfront exactly how bids will be valued.

This variation of the single auction approximates a situation in which the buyer knows (or at least believes it knows) how product/service offering should be evaluated, and the buyer is open and explicit about this knowledge with the sellers. As with Variation #1 discussed previously, by not updating its estimates of α and β based on seller bids, the buyer in this variation is essentially relying exclusively on its own prior information about what type of product/service will deliver the most value and ignoring any information that the sellers might possess.

In this variation, the contractors know precisely how their bids will be evaluated and they will use this information to formulate their bids. In particular, any seller j knows that the buyer will assign his bid (x_j,y_j,P_j) a value $v_j = \alpha_b x_j + \beta_b y_j - P_j$. Thus, it is the objective of any contractor j in this variation of the single auction to submit a bid with $P_j = C_j$ and to also:

$$
\begin{aligned}
&\text{Choose } x_j \text{ and } y_j \text{ to maximize } \alpha_b x_j + \beta_b y_j - P_j \\
&\Rightarrow \text{Choose } x_j \text{ and } y_j \text{ to maximize } \alpha_b x_j + \beta_b y_j - C_j \\
&\Rightarrow \text{Choose } x_j \text{ and } y_j \text{ to maximize } \alpha_b x_j + \beta_b y_j - \left(a_j x_j^2 + b_j y_j^2\right) \\
&\Rightarrow \text{Choose } x_j \text{ and } y_j \text{ to maximize } \left(\alpha_b x_j - a_j x_j^2\right) + \left(\beta_b y_j - b_j y_j^2\right)
\end{aligned}
$$

This maximization problem is solved in the same manner as previously done. In a result that parallels previous results, we find that each contractor j's optimal strategy is to submit a bid $(x_j,y_j,P_j,)$ in the "publish / no update" variation of the single auction such that:

$$x_j = \frac{\alpha_b}{2a_j}$$

$$y_j = \frac{\beta_b}{2b_j}$$

$$P_j = a_j x_j^2 + b_j y_j^2$$

As already noted, the winning seller in this variation will be the one whose bid maximizes the buyer's perceived overall value according to its prior estimates α_b and β_b (i.e., the bid which maximizes $v_j = \alpha_b x_j + \beta_b y_j - P_j$).

4. Variation #4: Publish / Update

The final variation of the single procurement auction is one in which the buyer publishes its own prior estimates of the weights α and β, but ultimately evaluates the bids based on updated estimates of those weights. This variation of the single auction approximates a situation in which the buyer waits until the bids are submitted to determine its ultimate evaluation criteria (i.e., the final weights it will place on each dimension of quality), but nonetheless chooses to communicate its own prior estimates of those weights before the auction, allowing sellers to incorporate this additional information into their bids. It is important to note in this variation that the estimated weights announced ex ante are different from the weights actually employed ex post to evaluate bids, which in actual practice, could increase protest risk.

In this variation, the sellers have an opportunity to update their own estimates of α and β (using the estimates published by the buyer) prior to submitting their bids. In particular, a contractor j will update its estimates of α and β by calculate weighted-averages between its own estimates (α_j and β_j) and the estimates published by the buyer (α_b and β_b). The weights assigned to each prior estimate will be the number of draws from the urn (either m_s or m_b) associated with the estimates. Thus, seller j's updated estimates of α and β are given by:

$$\hat{\alpha}_j = \frac{m_b\alpha_b + m_s\alpha_j}{m_b + m_s}$$
$$\hat{\beta}_j = \frac{m_b\beta_b + m_s\beta_j}{m_b + m_s}$$

To formulate its bid, each seller will solve the usual optimization problem using these updated estimates, yielding an optimal bid (x_j,y_j,P_j) which satisfies:

$$x_j = \frac{\hat{\alpha}_j}{2a_j}$$
$$y_j = \frac{\hat{\beta}_j}{2b_j}$$
$$P_j = a_j x_j^2 + b_j y_j^2$$

As in the original I^2A^2 mechanism, the buyer can re-estimate the true values of α and β in this variation of the single auction based on the bids submitted by contractors. The mathematics of this re-estimation are more complicated in this case, however, because the buyer must first extract each seller's individual updated estimates $\hat{\alpha}_j$ and $\hat{\beta}_j$ and then, from these individual updated estimates, the buyer must extract each seller's original estimates αj and βj. Nonetheless, the buyer can still infer any contractor j's estimates of αj and βj from its bid (xj, yj, Pj) (we will forgo the mathematical demonstration of this inference in the interest of brevity). Combining these estimates with the buyer's own estimates, αb and βb, allows the buyer to generate updated estimates of α and β as was done in the I^2A^2 mechanism:

$\hat{\alpha}$ = updated estimate of α

$\hat{\beta}$ = updated estimate of β

$$\hat{\alpha} = \frac{m_b \alpha_b + m_s \sum_{j=1}^{N} \alpha_j}{m_b + N m_s}$$

$$\hat{\beta} = \frac{m_b \beta_b + m_s \sum_{j=1}^{N} \beta_j}{m_b + N m_s}$$

In this variation, the winning seller's bid maximizes the buyer's perceived overall value according to these updated estimates of α and β. Thus, the buyer will assign any bid (xj,yj,Pj) a value $v_j = \hat{\alpha} x_j + \hat{\beta} y_j - P_j$, and the winning bid will be the one which maximizes this value.

G. Comparing the Estimation Accuracy of Alternatives

To this point, we have fully characterized the expected behavior and outcomes under the I^2A^2 mechanism as well as under four different variations of the traditional single auction alternative. To assess the value of the proposed I^2A^2 mechanism, however, we must identify and compare measures of performance across the various alternatives; the ultimate measure of performance from the buyer's perspective is the overall value that is delivered.

The particular procurement environment we are investigating is one in which there is significant uncertainty, at least initially, about the manner and the degree to which any procured product/service will deliver value to the buyer. Both the seller's ability to deliver value and the buyer's ability to assess value are constrained by the information they possess about the marginal benefit of different dimensions of quality—about the true values of the parameters α and β.

Consequently, one important measure by which to compare the alternative procurement mechanisms is the accuracy of the parameter estimates used by the buyer and sellers under each mechanism. In other words, how well do the sellers know what the buyer wants when they place their bids, and how well does the buyer know what it wants when it selects from among these bids? The more accurate the estimates of α and β, the better calibrated will be the sellers' bids and the buyers' selection process.

To begin this comparison, the table below lists, for each procurement alternative, (1) the parameter estimates used by the sellers when submitting their bids (more specifically, their final bids under the I^2A^2 mechanism), and (2) the parameter estimates used by the buyer when selecting a winner from among these bids.

Table 4. Seller and Buyer Parameter Estimates under Procurement Alternatives

Procurement Alternative	Estimates Used for Final Bid		Estimates Used to Select Winner	
	Estimate of α	Estimate of β	Estimate of α	Estimate of α
Single-Auction Variation #1: No Publish / No Update	α_j Seller's Prior Estimate	β_j Seller's Prior Estimate	α_b Buyer's Prior Estimate	β_b Buyer's Prior Estimate
Single-Auction Variation #2: No Publish / Update	α_j Seller's Prior Estimate	β_j Seller's Prior Estimate	$\frac{m_b\alpha_b + m_s\sum_{j=1}^{N}\alpha_j}{m_b + Nm_s}$	$\frac{m_b\beta_b + m_s\sum_{j=1}^{N}\beta_j}{m_b + Nm_s}$
Single-Auction Variation #3: Publish / No Update	α_b Buyer's Prior Estimate	β_b Buyer's Prior Estimate	α_b Buyer's Prior Estimate	β_b Buyer's Prior Estimate
Single-Auction Variation #4: Publish / Update	$\frac{m_b\alpha_b + m_s\alpha_j}{m_b + m_s}$	$\frac{m_b\beta_b + m_s\beta_j}{m_b + m_s}$	$\frac{m_b\alpha_b + m_s\sum_{j=1}^{N}\alpha_j}{m_b + Nm_s}$	$\frac{m_b\beta_b + m_s\sum_{j=1}^{N}\beta_j}{m_b + Nm_s}$
Iterated Information Aggregation Auction (I^2A^2)	$\frac{m_b\alpha_b + m_s\sum_{j=1}^{N}\alpha_j}{m_b + Nm_s}$	$\frac{m_b\beta_b + m_s\sum_{j=1}^{N}\beta_j}{m_b + Nm_s}$	$\frac{m_b\alpha_b + m_s\sum_{j=1}^{N}\alpha_j}{m_b + Nm_s}$	$\frac{m_b\beta_b + m_s\sum_{j=1}^{N}\beta_j}{m_b + Nm_s}$

Among the 20 cells in Table 4 above, there are four different estimates of α and four corresponding or parallel estimates of β. To compare the accuracy of these estimates, recall that these estimates are each based on a number of independent observations from a binomial distribution— the "draws from the urn" metaphor that was described previously. Consequently, the accuracy of any one of these estimates will depend directly on the number of independent observations or draws from the urn that are incorporated into the estimate—the greater the number of observations, the more accurate the estimate.

To further our comparison, Table 5 below lists the number of observations and resulting accuracy ranking for each corresponding pair of α and β estimates. For purposes of the table, we have assumed that $m_b > m_s$, or that the buyer has more information than any individual seller about the ultimate determinants of quality. We have assumed $m_b > m_s$ rather than the opposite, not only because it arguably holds true (at least marginally) in most cases, but also because any bias it introduces is a bias *against* the proposed I^2A^2 mechanism.

Table 5. Observations Aggregated and Accuracy Ranking of Parameter Estimates

Estimate of α	Estimate of β	Observations Aggregated	Accuracy Ranking
$\frac{m_b\alpha_b + m_s\sum_{j=1}^{N}\alpha_j}{m_b + Nm_s}$	$\frac{m_b\beta_b + m_s\sum_{j=1}^{N}\beta_j}{m_b + Nm_s}$	$m_b + Nm_s$	1st
$\frac{m_b\alpha_b + m_s\alpha_j}{m_b + m_s}$	$\frac{m_b\beta_b + m_s\beta_j}{m_b + m_s}$	$m_b + m_s$	2nd
α_b	β_b	m_b	3rd (Assuming $m_b > m_s$)
α_j	β_j	m_s	4th (Assuming $m_b > m_s$)

While Table 5 presents an ordinal ranking of the parameter estimates, it is valuable before proceeding to make some observations about the degree of difference in accuracy between the various estimates. As noted previously, it may not always be the case that $m_b > m_s$ and, even when this inequality holds, the difference may be minimal. Consequently, the difference in observations and accuracy between the third and fourth-ranked estimates above could be only marginal. The difference between the second and third-ranked estimates above could be somewhat more significant, as $m_b + m_s$ could be two or more times as large as m_b; however, our assumption that $m_b > m_s$ implies that there are less than twice the number of observations for the second-ranked estimates above as for the third-ranked estimates. Finally, and most importantly, the difference between the first and second-ranked estimates above, at least in terms of number of observations, is the most significant, as $m_b + Nm_s$ could be several times as large as $m_b + m_s$.

With the ranking of the various estimates in hand, we can now proceed to rank the various procurement alternatives in terms of overall accuracy. Thus, Table 6 presents, for each procurement alternative, (1) the ranking of estimates used by sellers when submitting their final bid, (2) the ranking of estimates used by the buyer when selecting a winner from among these bids, and (3) a combined overall accuracy ranking.

Table 6. Accuracy Ranking of Procurement Alternatives

Procurement Alternative	Ranking of Estimates Used for Final Bid	Ranking of Estimates Used to Select Winner	Overall Accuracy Ranking
Single-Auction Variation #1: No Publish / No Update	4th	3rd	5th
Single-Auction Variation #2: No Publish / Update	4th	1st	3rd
Single-Auction Variation #3: Publish / No Update	3rd	3rd	4th
Single-Auction Variation #4: Publish / Update	2nd	1st	2nd
Iterated Information Aggregation Auction (I^2A^2)	1st	1st	1st

In most cases, the overall accuracy ranking of a procurement alternative is easily determined; however, the relative positioning of the “no publish / update” and “publish / no update” alternatives is slightly less straightforward. Nonetheless, the previous discussion regarding the degree of difference in accuracy between various measures dictated that the former be ranked third and the latter ranked fourth.

The most important result presented in Table 6 is that the I^2A^2 mechanism clearly comes out as the top-rated alternative in terms of the accuracy of parameter estimates used in the process of bidding and bid selection. The accuracy advantage of the I^2A^2 mechanism over the other alternatives depends primarily on the number of sellers (N) and the amount of information possessed by those sellers (m_s)—the larger either variable, the greater the advantage.

H. Simulating the Procurement Alternatives

The previous section provided a general qualitative comparison among the procurement alternatives and concluded that the I^2A^2 mechanism is expected to provide better calibrated bidding and bid selection and, consequently, deliver greater overall value to the buyer. The magnitude of this advantage, however, was left undetermined. In this section, we will simulate the various procurement alternatives to provide quantitative measures comparing the various mechanisms.

To observe and measure the performance of the I^2A^2 mechanism and other procurement alternatives, we conducted mathematical simulations of a series of scenarios matching the procurement environment modeled above. The outcome under each of the five different procurement alternatives was recorded and evaluated for each simulated scenario.

1. Input Parameters

The simulation analysis involved a total of 150,000 trials conducted using the Crystal Ball simulation add-in program for Microsoft Excel. Figure 5 below summarizes the basic parameter inputs into Excel for each such trial. To understand the relationship between the simulation trials and the model described above, each key input parameter in the figure is labeled in red with its corresponding parameter value as described in our previous model analysis.

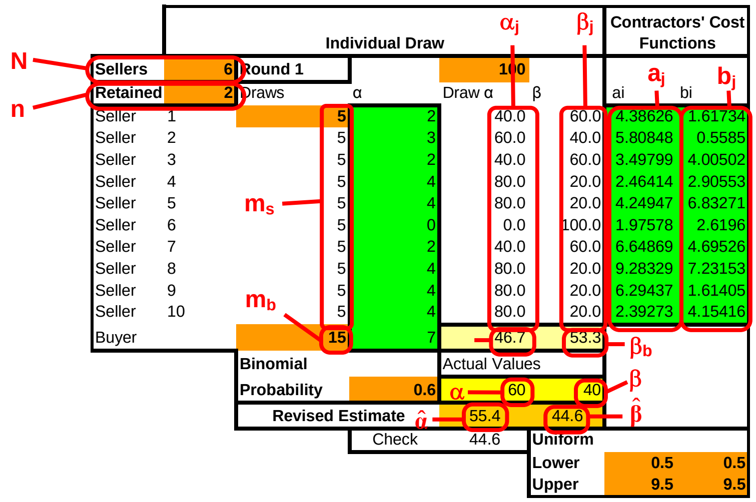

Figure 5. Simulation Input Parameters as Displayed in Microsoft Excel

The fundamental parameters varied in each trial were the underlying quality parameters α and β as well as the cost parameters for each contractor a_j and b_j. For each trial, the quality parameter α was randomly drawn from a uniform distribution between 0 and 100, with the quality parameter β then set equal to $100-\alpha$. Values of a_j and b_j for each contractor were similarly randomly drawn each trial from a uniform distribution between 0.5 and 9.5.

With these basic parameters randomly drawn, further random draws determined the buyer and seller prior estimates of α and β for each trial. The buyer's estimate α_b was determined by simulating m_b draws from a binomial distribution with a probability corresponding to the true value of α previously determined, with β_b then set equal to $100-\alpha_b$. Similarly, each seller's estimate α_j was determined by simulating m_s draws from a binomial distribution with a probability corresponding to the true value of α previously determined, with β_j then set equal to 100-α_j. The updated estimates $\hat{\alpha}$ and $\hat{\beta}$ were calculated according to the formulas presented previously.

The values for m_b and m_s (the number of "draws from the urn" for the buyer and sellers, respectively) as well as the values for N (the total number of sellers) and n (the number of sellers retained after the initial auction in the I^2A^2 mechanism) were pre-determined for each trial. Each of these four variables (m_b, m_s, N, and n) took one of two possible values during the simulations with the six different variations of variable values illustrated in Table 7. A total of 25,000 simulation trials were conducted for each variation.

Table 7. Procurement Simulation Variations

	Simulation #					
	1	***2***	***3***	***4***	***5***	***6***
Buyer's Draws	15	15	5	5	15	15
Sellers' draws	15	15	15	15	5	5
Beginning Sellers'	10	4	10	4	10	4
Retained Sellers'	5	2	5	2	5	2

We were interested in observing outcomes under various information conditions and therefore, as seen from Table 7, two of the simulation variations modeled the buyer and each seller with an equal number of draws (m_b=m_s=15), two of the variations modeled the buyer with fewer draws (less information) than each seller (m_b=5, m_s=15), and two of the variations modeled the buyer with more draws (more information) than each seller (m_b=15, m_s=5).

We were also interested in observing outcomes under various levels of competition (different numbers of sellers) and therefore, as again seen from Table 7 above, half the simulation variations involved 10 total sellers (N=10), while half involved only 4 total sellers (N=4). In each variation, only 50% of the total buyers were retained after the initial auction in the I^2A^2 mechanism.

2. Bids, Values, and Winners

A series of intermediate “process” variables were calculated for each procurement alternative for each of the 150,000 simulation trials conducted. Figure 6 below illustrates these intermediate variables for a single trial as viewed in Excel for two of the five procurement alternatives: The “publish / no update” variation (on the left) and “publish / update” variation (on the right) of the single procurement auction.

Option 3: Buyer Publishes
Buyer ex ante Weights

X	Y	P	Perceived Gov Value	Actual Gov Value	Rank		
5.3	16.5	$ 564	$ 564	$ 415	2		1
4.0	47.7	$ 1,367	$ 1,367	$ 784	1	1	
6.7	6.7	$ 333	$ 333	$ 333	5		
9.5	9.2	$ 466	$ 466	$ 470	4		
5.5	3.9	$ 232	$ 232	$ 253	6		
11.8	10.2	$ 547	$ 547	$ 569	3		
			$ 1,367	$ 784			
		Buyer Surplus	$ 564	$			
		Seller Surplus	$ 803				
		Check	$ 1,367				

Seller bids

Value given actual α & β values

Value given buyer ex-post estimates of α & β

Actual buyer surplus

Perceived buyer surplus

Supplier surplus

Perceived total surplus

Option 4: One Stage-Buyer Publishes & Updates
Buyer ex post Weights

α	β	X	Y	P	Perceived Gov Value	Actual Gov Value	Rank		
45.0	55.0	5.1	17.0	$ 583	$ 460	$ 405	4		
50.0	50.0	4.3	44.8	$ 1,227	$ 1,009	$ 822	1	1	
45.0	55.0	6.4	6.9	$ 334	$ 329	$ 327	5		
55.0	45.0	11.2	7.7	$ 481	$ 482	$ 498	3		
55.0	45.0	6.5	3.3	$ 252	$ 253	$ 268	6		
35.0	65.0	8.9	12.4	$ 558	$ 486	$ 469	2		1
					$ 1,009	$ 822			
				Buyer Surplus	$ 486	$ 299			
				Seller Surplus	$ 523				
				Check	$ 1,009				

Sellers’ updated estimates of α & β values

Figure 6. Simulation Process Variables as Displayed in Microsoft Excel

First of all, bids of the form (xj,yj,Pj) were calculated for each seller in each trial and for each procurement alternative. In the “publish / update” variation of the single procurement auction, this first requires calculating an updated weighted-average re-estimation of α and β, as described previously and as illustrated in the right side of Figure 6. Seller bids for all other procurement alternatives were calculated using either seller prior estimates (αj and βj), buyer prior estimates (αb and βb), or buyer updated estimates ($\hat{\alpha}$ and $\hat{\beta}$), which were calculated and shown previously in Figure 5.

Next, the buyer’s *perceived* value was calculated for each seller bid, with the perceived value based on either the buyer’s prior or updated estimates of α and β, depending on the procurement alternative. For the I^2A^2 mechanism as well as the “no publish / update" and "publish / update" variations of the single procurement auction, the buyer uses updated estimates of α and β to value seller bids; thus the value assigned to seller j's bid was $v_j = \hat{\alpha}x_j + \hat{\beta}y_j - P_j$ under each of these three alternatives. For the "no publish / no update" and "publish / no update" variations of the single procurement auction, the buyer uses its prior estimates of α and β to value seller bids, thus the value assigned to seller j's bid was vj=αbxj+βbyj-Pj under each of these two alternatives. In each trial and for each procurement alternative, the *actual* or true value of each seller's bid was also calculated using the true (but unknown) values of α and β, assigning to each seller j's bid a value of $v_j = \alpha x_j + \beta y_j - P_j$.

Next, the seller bids were ranked according to the buyer's perceived value and the winning and second-place bids were identified. Recall that a generalized second-price auction is employed, so the price paid to the winning seller in each trial and for each alternative was the price bid by the winning seller plus the difference in value between the first-place and second-place bids.

3. Buyer Surplus, Seller Surplus, and Total Surplus

The final set of intermediate variables shown in Figure 6 and calculated for each trial and each procurement alternative involves buyer and seller surplus. Buyer surplus is generally defined as the value of the product/service received minus the price paid, while supplier surplus is defined as price received minus the cost incurred. To facilitate the explanation of how these variables are calculated in the simulation, the following definitions and notation are helpful:

(x_1, y_1, P_1)	= winning bid
q_1	= perceived quality of winning bid
	= $\hat{\alpha}x_1 + \hat{\beta}y_1$ under I^2A^2, "no publish / update" & "publish / update"
	= $\alpha_b x_1 + \beta_b y_1$ under "no publish / no update" & "publish / no update"
q^*	= true quality of winning bid
	= $\alpha x_1 + \beta y_1$
v_1	= perceived value of winning bid
	= $q_1 - P_1$
v_2	= perceived value of second-place bid

C_1 = cost of winning bid
$= P_1$
P^* = price paid to winning seller (under generalized second-price auction)
$= P_1 + v_1 - v_2$
$= P_1 + (q_1 - P_1) - v_2$
$= q_1 - v_2$

With the notion of quality described above, we can redefine buyer surplus as quality minus price paid. Thus, the two notions of buyer surplus (perceived and actual) were calculated in the simulations as follows:

Perceived buyer surplus = Perceived quality minus price paid
$= q_1 – P^*$
$= q_1 - (q_1 - v_2)$
$= v_2$

Actual buyer surplus = Actual quality minus price paid
$= q^* – P^*$
$= q^* - (q_1 - v_2)$
$= v_2 + q^* - q_1$

Thus, perceived buyer surplus and actual buyer surplus will differ by the amount the buyer is "off" in its perception of the quality of the product/service it is receiving. If the buyer overestimates the quality of the winning bid, actual surplus will be less than perceived surplus. If the buyer underestimates the quality of the winning bid, actual surplus will be greater than perceived surplus. Note, however, that the buyer is more likely to have overestimated than to have underestimated the quality of the winning bid because a significant underestimate of the quality of the winning bid would result in a different bid being ranked first among the seller bids. Consequently, it will more often be the case that the actual buyer surplus is less than the perceived buyer surplus than vice versa.

To understand the calculation of seller surplus, we can use the fact that the winning seller bids $P_1 = C_1$. Also note that there is no "perceived" seller surplus because, unlike the buyer, the seller is assumed to have no uncertainty about its incentives (about its cost function). Thus, we have

$$
\begin{aligned}
\text{Seller surplus} &= \text{Price received minus cost incurred} \\
&= P^* - C_1 \\
&= P_1 + v_1 - v_2 - C_1 \\
&= P_1 + v_1 - v_2 - P_1 \\
&= v_1 - v_2
\end{aligned}
$$

Finally, total surplus is simply defined as the sum of buyer and seller surplus. Thus, we have

$$
\begin{aligned}
\text{Perceived total surplus} &= \text{Perceived buyer surplus + seller surplus} \\
&= v_2 + (v_1 - v_2) \\
&= v_1 \\
&= q_1 - P_1
\end{aligned}
$$

$$
\begin{aligned}
\text{Actual total surplus} &= \text{Actual buyer surplus + seller surplus} \\
&= v_2 + q^* - q_1 + (v_1 - v_2) \\
&= v_1 + q^* - q_1 \\
&= (q_1 - P_1) + q^* - q_1 \\
&= q^* - P_1
\end{aligned}
$$

4. Summary Statistics for an Individual Trial

After calculating the input parameters, bids, winner, and surpluses for each procurement alternative for an individual trial, the simulation produced the most important information to be extracted from the trial: Summary statistics to compare alternatives. A sample of these summary statistics is provided in Figure 7.

		Perceived Buyer Surplus	Actual Buyer Surplus	Seller Surplus	Actual Total Surplus	Seller	Seller Chooses X, Y α	Seller Chooses X, Y β	Buyer Evaluates X, Y α	Buyer Evaluates X, Y β	X	Y	P	Perceived Buyer Surplus	Actual Buyer Surplus	Seller Surplus	Actual Total Surplus	Consis-tency
Option 1	Buyer Doesn't Publish Buyer *ex ante* Weights	$ 554	$ 146	$ 725	$ 871	2	*60.0*	*40.0*	46.7	53.3	5.2	35.8	$ 871	110.24%	28.99%	196.98%	100.00%	1
Option 2	Buyer Doesn't Publish Buyer ex post Weights	$ 432	$ 291	$ 580	$ 871	2	60.0	40.0	55.4	44.6	5.2	35.8	$ 871	85.99%	57.86%	157.55%	100.00%	1
Option 3	Buyer Publishes Buyer ex ante Weights	$ 564	$ (19)	$ 803	$ 784	2	*46.7*	*53.3*	46.7	53.3	4.0	47.7	$ 1,367	112.11%	-3.83%	218.11%	89.99%	1
Option 4	One Stage-Buyer Publishes Buyer ex post Weights	$ 482	$ 296	$ 526	$ 822	2	*50.0*	*50.0*	55.4	44.6	4.3	44.8	$ 1,227	95.93%	58.80%	142.94%	94.37%	1
Option 5	Two Stage-Buyer Updates Buyer *ex post* Weights	$ 483	$ 320	$ 541	$ 861	2	55.4	44.6	55.4	44.6	4.8	39.9	$ 1,023	95.95%	63.66%	146.78%	98.80%	1
	Perfect Information	$ 503	$ 503	$ 368	$ 871	2	60	40	60	40	12.2	6.9	$ 503					

% of perfect info outcome

Does winning seller match perfect info outcome?

Figure 7. Summary Statistics for an Individual Trial as Displayed in Microsoft Excel

The most important summary statistics are highlighted in the last few columns of the chart in Figure 7 and were calculated by comparing the outcome under each procurement alternative with the outcome under a “perfect information” procurement auction. The perfect information procurement auction is one in which there is no uncertainty; the buyer and all sellers know the precise values of α and β throughout the process. The outcome under this hypothetical scenario is displayed in the bottom row of Figure 7.

Any of the procurement alternatives conducted in a perfect information environment would guarantee that the buyer receives the absolutely highest value (true quality minus true cost) product/service that can be produced by any of the available sellers, and that, correspondingly, the seller that can meet the buyer’s needs most efficiently wins the auction. Furthermore, the highest possible total surplus would always be realized in a perfect information environment. In this way, the perfect information procurement auction represents an ideal benchmark (although purely hypothetical and unachievable) against which to evaluate each of the procurement alternatives.

Thus, the most important summary statistics for any individual trial convey the level of each surplus (perceived buyer surplus, actual buyer surplus, seller surplus, and total surplus) actually achieved under each procurement alternative as a percentage of the same surplus that would be achieved under the perfect information scenario. These percentages are shown on the right hand side of Figure 7.

In the very last column of Figure 7 is a summary statistic labeled “consistency.” This indicates whether the winning seller under a given procurement alternative is the seller that would have been chosen under the perfect information scenario. Thus, the consistency measure can be understood as an indication of whether a particular procurement alternative has chosen the “correct” contractor from whom a product/service should be procured.

5. Summary Statistics Across All Trials

Having described the summary statistics as calculated for an individual simulation trial, we are now prepared to examine the summary statistics averaged across all 25,000 trials for each simulation variation. These average statistics for each procurement alternative and each simulation variation are provided in Table 8.

Table 8. Summary Statistics by Procurement Alternative and Simulation Variation

	Simulation Variation						
Auction Option	1	2	3	4	5	6	Mean
No publish choice ex ante (O-1)							
Mean perceived buyer surplus	97.71	94.16	103.23	95.03	89.89	85.01	94.17
Mean actual buyer surplus	80.64	81.68	63.26	62.26	70.47	68.31	71.10
Perceived less actual	17.07	12.48	39.97	32.77	19.42	16.7	23.07
Mean total surplus	89.64	90.78	84.96	86.7	81.84	81.66	85.93
Consistency	25	19	32	26	32	26	26.67
No publish choice ex post (O-2)							
Mean perceived surplus	95.71	94.95	95.79	95.02	88.42	86.07	92.66
Mean actual surplus	92.71	91.98	92.78	92.19	80.83	78.95	88.24
Perceived less actual	3	2.97	3.01	2.83	7.59	7.12	4.42
Mean total surplus	94.2	94.04	94.26	94	85.71	84.79	91.17
Consistency	10	8	10	8	22	19	12.83
Publish choice ex ante (O-3)							
Mean perceived surplus	108.27	105.62	123.36	117.2	108.09	105.53	111.35
Mean actual surplus	77.62	76.07	41.75	32.92	78.04	75.85	63.71
Perceived less actual	30.65	29.55	81.61	84.28	30.05	29.68	47.64
Mean total surplus	90.18	91.8	76.1	77.78	90.4	91.61	86.31
Consistency	20	13	26	19	19	13	18.33
Publish choice ex post (O-4)							
Mean perceived surplus	98.46	97.95	97.12	96.51	98.94	97.95	97.82
Mean actual surplus	95.54	94.98	94.12	93.69	91.61	91.08	93.50
Perceived less actual	2.92	2.97	3	2.82	7.33	6.87	4.32
Mean total surplus	96.64	96.76	97.11	95.28	94.49	94.71	95.83
Consistency	8	5	10	8	11	8	8.33
Multi-stage auction (O-5)							
Mean perceived surplus	100.83	99.7	100.87	99.77	100.1	95.93	99.53
Mean actual surplus	97.89	96.78	97.87	96.89	92.74	88.99	95.19
Perceived less actual	2.94	2.92	3	2.88	7.36	6.94	4.34
Mean total surplus	98.88	99.03	98.83	98.92	96.55	96.03	98.04
Consistency	7	5	7	7	13	12	8.50

Comparisons across variations will be discussed in some detail below, so it is helpful at this point to focus on the last column in Table 8, which provides the mean statistics across all variations for the five procurement alternatives.

Because the buyer is generally the party that chooses among procurement alternatives, it is perhaps most instructive to look at what is at stake for the buyer and compare the "mean actual buyer surplus" across the alternatives. With a mean buyer surplus of 95.2% of the perfect information outcome, the I^2A^2 mechanism outperforms the four single-auction alternatives, which achieve mean buyer surpluses of 71.1%, 88.2%, 63.7%, and 93.5%.

The I^2A^2 mechanism also significantly outperforms the four single auction alternatives in terms of total surplus with a mean of 98.0% of the perfect information outcome vs. 85.9%, 91.2%, 86.3%, and 95.8% for the single-auction variations. The I^2A^2 mechanism's consistency measure was also significantly better than all but one of the single-auction variations.

A key factor from Table 8 appears to be the buyer using updated estimates to choose among bids, as the two alternatives in which the buyer relied only on its own prior estimates of the quality parameters resulted in perceived buyer surplus values 23.1 and 47.6 percentage points higher than the actual buyer surplus. Under the three alternatives in which the buyer used updated estimates, in contrast, perceived buyer surplus differed from actual buyer surplus by only 4.4, 4.3, and 4.3 percentage points.

6. The I^2A^2 Mechanism vs. the Single-Auction Alternatives

To further investigate the advantages of the I^2A^2 mechanism over the single-auction alternatives, this section will compute the "delta" or improvement afforded by the I^2A^2 mechanism across the various performance metrics. This delta will be calculated as a percentage of the metric's value under the single-auction alternative to which the comparison is being made.

To start, let us measure the degree of improvement provided by the I^2A^2 mechanism over the average of all four single-auction alternatives. This comparison is presented in Table9 below.

Table 9. The I^2A^2 Mechanism vs. All Four Single-Auction Variations

	1	2	3	4	5	6	Mean
Mean Single-stage Auction							
Mean actual surplus	86.63	86.18	72.98	70.27	80.24	78.55	79.14
Perceived less actual	13.41	11.9925	31.8975	30.675	16.0975	15.0925	19.86
Consistency	15.75	11.25	19.5	15.25	21	16.5	16.54
Mean total surplus	92.665	93.345	88.1075	88.44	88.11	88.1925	89.81
Multi-stage Delta							
Mean actual surplus	0.1300	0.1230	0.3411	0.3789	0.1558	0.1329	0.2103
Perceived less actual	-0.7808	-0.7565	-0.9059	-0.9061	-0.5428	-0.5402	-0.7387
Consistency	-0.5556	-0.5556	-0.6410	-0.5410	-0.3810	-0.2727	-0.4911
Mean total surplus	0.0671	0.0609	0.1217	0.1185	0.0958	0.0889	0.0921

Observe that the I^2A^2 mechanism achieves 21% more actual buyer surplus and 9% more total surplus than the average single procurement auction. The I^2A^2 mechanism also cuts in half (down 49%) the frequency with which a "wrong" (or inefficient) seller is selected. Significantly contributing to these results is the fact that the I^2A^2 mechanism reduces the amount by which the buyer overestimates the value delivered by the winning bidder by a dramatic 74%.

These results may actually understate the improvement promised by the I^2A^2 mechanism, however, because the best performing single-auction alternative—the "publish / update" variation (variation #4)—may not be allowed under federal law. In particular, the "publish / update" option involves publishing or announcing preliminary decision criteria (the buyer's prior estimates of α and β), which differ from the ultimate decision criteria (updated estimates of α and β) that are used to select the auction winner. Our understanding of *FAR* section 15.301 ("Proposal Evaluation") of the *Federal Acquisition Regulation* suggests that such a procedure would be prohibited from use by federal contracting officers.

Thus, it is perhaps better to measure the degree of improvement provided by the I^2A^2 mechanism over the average of the "permissible" single-auction variations #1 through #3. This comparison is presented in Table 10.

Table 10. The I^2A^2 Mechanism vs. Single-Auction Variations #1 - #3

	1	2	3	4	5	6	Mean
Mean Single-stage Auction							
Mean actual surplus	83.66	83.24	65.93	62.46	76.45	74.37	74.35
Perceived less actual	16.91	15.00	41.53	39.96	19.02	17.83	25.04
Consistency	18.33	13.33	22.67	17.67	24.33	19.33	19.28
Mean total surplus	91.34	92.21	85.11	86.16	85.98	86.02	87.80
Multi-stage Delta							
Mean actual surplus	0.1701	0.1626	0.4845	0.5513	0.2131	0.1966	0.30
Perceived less actual	-0.8396	-0.7810	-0.8676	-0.8370	-0.6975	-0.6410	-0.78
Consistency	-0.62	-0.63	-0.69	-0.60	-0.47	-0.38	-0.56
Mean total surplus	0.0825	0.0740	0.1612	0.1481	0.1229	0.1164	0.12

Observe that the I^2A^2 mechanism now achieves fully 30% more actual buyer surplus and 12% more total surplus than the average of the three remaining single-auction variations. The I^2A^2 mechanism also reduces the frequency with which the "wrong" (or inefficient) seller is selected by more than half (down 56%). Again, significantly contributing to these results is the fact that the I^2A^2 mechanism reduces by fully 78% the amount by which the buyer overestimates the value delivered by the winning bidder.

Finally, it may also be valuable to specifically compare the I^2A^2 mechanism to single-auction variation #3, the "publish / no update" alternative. This comparison is particularly important because it is the "publish / no update" variation which appears to correspond most closely with the approach encouraged by status quo *FAR* policy: The buyer fully articulates the criteria in advance and uses these same criteria to evaluate the bids submitted. This comparison between the I^2A^2 mechanism and the "publish / no update" single-auction variation is presented in Table 11.

Table 11. The I^2A^2 Mechanism vs. the "Publish / No Update" Variation

Publish choice ex ante (O-3)							
Mean actual surplus	77.62	76.07	41.75	32.92	78.04	75.85	63.71
Perceived less actual	30.65	29.55	81.61	84.28	30.05	29.68	47.64
Mean total surplus	90.18	91.8	76.1	77.78	90.4	91.61	86.31
Consistency	20	13	26	19	19	13	18.33
Multi-stage Delta							
Mean actual surplus	0.2611	0.2722	1.3442	1.9432	0.1884	0.1732	0.6971
Perceived less actual	-0.9041	-0.9012	-0.9632	-0.9658	-0.7551	-0.7662	-0.8759
Mean total surplus	0.0965	0.0788	0.2987	0.2718	0.0680	0.0482	0.1437
Consistency	-0.6500	-0.6154	-0.7308	-0.6316	-0.3158	-0.0769	-0.5034

When compared to this status quo policy alternative, the I^2A^2 mechanism represents a truly eye-opening improvement. The I^2A^2 mechanism achieves fully 70% more actual buyer surplus and 14% more total surplus than the "publish / no update" variation. The I^2A^2 mechanism continues to reduce the frequency with which a "wrong" (or inefficient) seller is selected by half (down 50%), and reduces the amount by which the buyer overestimates the value delivered by the winning bidder by 88%. In fact, among all of the single-auction variations, the "publish / no update" alternative is the worst performer by most measures, suggesting that the I^2A^2 mechanism may represent a particularly significant improvement over the status quo in the presence of quality (or value) uncertainty.

7. The Influence of Varying Competition and/or Information

The analysis to this point clearly suggests that the I^2A^2 mechanism may provide significant opportunities for performance improvement over single-auction alternatives. For purposes of "real-world" application, however, we would like to know the conditions under which the I^2A^2 mechanism offers the greatest potential. For this reason, we also investigated the performance of all procurement alternatives under various levels of competition and information. In particular, the simulations were conducted under six different variations as described in Table 12.

Table 12. Levels of Competition and Information by Simulation Variation

	Simulation #					
Information & Competiton	1	2	3	4	5	6
Buyers' draws	15	15	5	5	15	15
Sellers' draws	15	15	15	15	5	5
Number of sellers' entering auction	10	4	10	4	10	4
Number of seller draws	150	60	150	60	50	20
Total number of draws	***165***	***75***	***155***	**65**	**65**	**35**

As shown in Table 12, simulation variations 1, 3, and 5 incorporated a high level of competition with 10 total sellers (underlined), while variations 2, 4, and 6 incorporated a low level of competition with only 4 total sellers. Meanwhile, simulation variations 1, 2, and 3 were the three highest-information scenarios with 165, 75, and 155 total "draws," respectively; variations 4, 5, and 6 were the three lowest-information scenarios with 65, 65, and 35 total "draws," respectively.

The improvement afforded by the I^2A^2 mechanism in high-competition vs. low-competition scenarios as well as in high-information vs. low-information scenarios is presented in Table 13. Note that Table 13 only includes the three single-auction variations that are not prohibited by regulation (variations #1 to #3).

Table 13. Improvement from I^2A^2 Mechanism as Competition & Information Vary

	1	2	3	4	5	6	Mean high-competion	Mean low-competion	Mean high-info draw	Mean low-info draw
Multi-stage auction										
Mean actual surplus	97.89	96.78	97.87	96.89	92.74	88.99	96.17	94.22	97.51	92.87
Perceived less actual	2.94	2.92	3.00	2.88	7.36	6.94	4.43	4.25	2.95	5.73
Mean total surplus	98.88	99.03	98.83	98.92	96.55	96.03	98.09	97.99	98.91	97.17
Consistency	7.00	5.00	7.00	7.00	13.00	12.00	9.00	8.00	6.33	10.67
Mean Single-stage Auction (Opt. 1-3)										
Mean actual surplus	83.66	83.24	65.93	62.46	76.45	74.37	75.34	73.36	77.61	71.09
Perceived less actual	16.91	15.00	41.53	39.96	19.02	17.83	25.82	24.26	24.48	25.60
Mean total surplus	91.34	92.21	85.11	86.16	85.98	86.02	87.48	88.13	89.55	86.05
Consistency	18.33	13.33	22.67	17.67	24.33	19.33	21.78	16.78	18.11	20.44
Multi-stage auction Improvement										
Mean actual surplus							0.28	0.28	0.26	0.31
Perceived less actual							-0.83	-0.82	-0.88	-0.78
Mean total surplus							0.12	0.11	0.10	0.13
Consistency							-0.59	-0.52	-0.65	-0.48

Observe that the degree of improvement provided by the I^2A^2 mechanism is virtually the same along most performance measures in both the high-competition and low-competition scenarios. On the other hand, the I^2A^2 mechanism offers greater improvement in the low-information scenarios than in the high-information scenarios. This suggests that the I^2A^2 mechanism may offer about the same benefits, regardless of the level of competition, but offers the greater benefits in low-information environments.

In addition to the overall level of information in the environment, it is also instructive to consider which side of the market possesses the most information. In particular, note from Table 12 that the buyer has less information than each individual seller in simulation variations 3 and 4, while the buyer has more information than each individual seller in simulation variations 5 and 6. This allows us to compare the improvement provided by the I^2A^2 mechanism under these two information-balance scenarios; the results of this comparison are presented in Table 14.

Table 14. Improvement from the I^2A^2 Mechanism as Information Balance Varies

	1	2	3	4	5	6	sellers' draws exceed buyer's	buyer's draws exceed sellers'
Multi-stage auction								
Mean actual surplus	97.89	96.78	97.87	96.89	92.74	88.99	97.38	90.87
Perceived less actual	2.94	2.92	3	2.88	7.36	6.94	2.94	7.15
Mean total surplus	98.88	99.03	98.83	98.92	96.55	96.03	98.88	96.29
Consistency	7	5	7	7	13	12	7.00	12.50
Mean Single-stage Auction (Opt. 1-3)								
Mean actual surplus	83.66	83.24	65.93	62.46	76.45	74.37	64.19	75.41
Perceived less actual	16.91	15.00	41.53	39.96	19.02	17.83	40.75	18.43
Mean total surplus	91.34	92.21	85.11	86.16	85.98	86.02	85.63	86.00
Consistency	18	13	23	18	24	19	20.17	21.83
Multi-stage auction Improvement								
Mean actual surplus							0.52	0.20
Perceived less actual							-0.93	-0.61
Mean total surplus							0.15	0.12
Consistency							-0.65	-0.43

First, observe from Table 14 that if the buyer were to conduct a single procurement auction, it would clearly prefer having more information than the individual sellers, as opposed to the opposite (75% vs. 64% actual buyer surplus). Contrarily, the situation is reversed under the I^2A^2 mechanism (91% actual buyer surplus when the buyer has more information vs. 98% when individual sellers have more information). This reflects the fact that the I^2A^2 mechanism fully aggregates the sellers' information, both to improve seller bids and to improve buyer bid selection, whereas the single auction variations generally do not.

More importantly, Table 14 indicates that the I^2A^2 mechanism offers significantly greater improvement over the single-auction alternatives when the sellers have better information relative to the buyer (52% increase in buyer surplus vs. only 20% when the buyer has more information). This strongly suggests that the I^2A^2 mechanism offers the greatest promise in environments in which contractors are likely to have more information about what type of product/service might best serve the buyer's needs. Such environments might include markets for relatively new products or services, markets in which technology is advancing rapidly, or markets in which the buyer is a relatively inexperienced consumer.

I. Conclusions

In this chapter we have introduced an integrated auction mechanism that endogenously addresses four key questions associated with any procurement decision:

1. *What* should be procured?
2. *How* it should be procured?
3. *From whom* it should be procured?
4. *At what price* it should be procured?

This mechanism is called the iterated information aggregation auction mechanism, or the I^2A^2 mechanism for short, and applies concepts from the field of mechanism design to overcome problematic incentive and information conditions that pervade procurement environments. In particular, the I^2A^2 mechanism is designed to truthfully extract and efficiently aggregate all relevant information in situations in which such information is incomplete, diffuse and private.

We have demonstrated that the design of the I^2A^2 mechanism induces sellers to truthfully reveal information about buyer value and seller cost, and it also offers the best product or service that can be profitably provided. Modeling the I^2A^2 mechanism relative to single procurement auction alternatives illustrated that the proposed mechanism promises significantly more accurate calibration of estimates both for sellers to offer the strongest bids and for the buyer to properly choose a winner from among those bids.

Finally, simulation analysis has revealed that the I^2A^2 mechanism offers the potential to provide the buyer 30% or more additional surplus (price minus true value) than the available single-auction alternatives and to dramatically reduce the problem of overestimating bid values, which is endemic to the single procurement auctions. Investigating the performance of the I^2A^2 mechanism under various competitive and information conditions, we further found that the mechanism performs comparably well under both high-competition and low-competition scenarios, but appears to be most valuable in environments with relatively low information, especially when contractors possess better information about the potential value of a product/service than the government buyer.

V. Compatibility in Auctions with Asymmetric Information

One form of information imperfection and asymmetry involves costs and the relative importance of product characteristics, as explored above. Another form of information asymmetry involves the fit between the buyer and seller. For a wide range of commercial arrangements, a high degree of compatibility between a buyer and seller raises the value of the contract for both parties. For instance, a good match between authors and their editors may generate a better selling book, and an athletic team is more likely to win games if the players have compatible skills. In some cases, compatibility is so important that it is the primary determinant of contract value. A recent study by accounting giant KPMG indicated that “83% of all mergers and acquisitions (M&As) failed to produce any benefit for shareholders and over half actually destroyed value.” Interviews of over 100 senior executives revealed that the overwhelming cause of failure was “the people and the cultural differences” or the poor quality of the match (Gitelson et al., 2001).

Given the impact of matching on contract value, it is not surprising that we observe sellers using matching as a factor in their choice of buyer. The problem in many cases is that the quality of the match may not be apparent until well after contracting has occurred. An author and editor may have an impression of how well they will work together, but neither party will be certain of their compatibility until after the publishing contract has been signed and work has begun.

The purpose of this study is to investigate what mechanism the seller should use to allocate contracts in situations in which matching is the primary determinant of contract value, but information about match quality is incomplete. We develop a model in which a single seller seeks to contract with one of several buyers. Each pairing of seller and buyer is characterized by a match, which determines each party’s value for the contract. The better the match, the more each party values the contract. We consider the following three information structures:

Complete information – For each pairing of seller and buyer, both the seller and buyer know the quality of the match. This case serves as a benchmark.

Informed seller – For each pairing of seller and buyer, only the seller knows the quality of the match. The buyer knows the distribution from which the match quality was drawn.

Informed buyer – For each pairing of seller and buyer, only the buyer knows the quality of the match. The seller knows the distribution from which the match quality was drawn.

For the complete information case, we show that the seller's best strategy is to approach the buyer with the best match quality and make a take-it-or-leave-it offer in the amount of the buyer's value for the contract. The contract is allocated efficiently and the seller captures the entire surplus. For the informed seller case, the seller should, once again, approach the buyer with the best match and make a take-it-or-leave-it offer. However, the buyer does not know the quality of the match in this case, so the amount of the offer is set to the buyer's expected value for the contract. For the informed buyer case, we show the seller should hold a first-price auction with an elevated reserve price. The auction not only stimulates competition among the buyers but also provides a vehicle through which the buyers can signal their private information to the uninformed seller. These results are developed in the sections that follow.

A. The Model

A seller offers a contract to one of n risk-neutral buyers (n = 2). Every potential pairing of seller and buyer has an associated match. We denote the match between the seller and buyer *i* by $\theta_i \in [\underline{\theta}, \overline{\theta}] \subset \mathbb{R}$, where $\theta_i > \theta_j$ indicating that buyer *i* has a better match than does buyer j. We assume the $\theta_i's$ are independently and identically distributed according to a commonly known cumulative distribution function (cdf) F with F ($\underline{\theta}$)= 0 and F $\overline{\theta}$ = 1.

Assumption 1: *F has positive density f at every* $\theta_i \in [\underline{\theta}, \overline{\theta}]$.

Buyer *i*'s utility from contracting with the seller is:

$\theta_i - t_i$,

where θ_i is buyer *i*'s value for the contract and $t_i \in \mathbb{R}$ is the payment made by buyer *i*. Buyer *i*'s utility is zero if not contracted with the seller.

The seller derives utility from both the payment and the match with the buyer. We assume the seller's utility from contracting with buyer i is:

$V(\theta_i) + t_i$,

where $V(\theta_i)$ represents the seller's value for the match with buyer *i*. The following assumption captures the notion that a good match raises the value of the contract for both the seller and the buyer:

Assumption 2: V $[\underline{\theta}, \overline{\theta}] \rightarrow \mathbb{R}$ *is continuous and strictly increasing over* $[\underline{\theta}, \overline{\theta}]$.

The seller's utility is zero if contracted with any buyer.[9]

If the seller were to contract with buyer *i*, the total economic surplus generated would be $V(\theta_i) + \theta_i$, where $V(\theta_i)$ represents the seller's value for contracting with buyer *i* and θ_i represents buyer *i*'s value for contracting with the seller. If the seller were to retain the contract, the total economic surplus generated would be zero. It follows that

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[9] When V (θ_i)= $v\theta_i$, where *v* is a positive constant, our model can be mapped to the interdependent valuations framework outlined in Section 5 of Jehiel and Moldovanu (2001): simply let the agents be indexed by *i* $\in$ {0, 1, 2, ..., n}, where agent *i* is the seller if *i* = 0 and buyer *i* otherwise; let p_k^i be the probability the contract is awarded to agent *i* in alternative *k*; and let
$s^0 = 0,\ s^i = \theta_i,\ a_{k0}^i = vp_k^i,\ a_{ki}^i = p_k^i,\ and\ a_{ki}^j = 0\ \ for\ all\ \ j \neq i.$

when the surplus generated is positive, a mutually beneficial trade exists. The following assumption is imposed so as not to rule out the possibility of such a mutually beneficial trade.

Assumption 3 (participation condition): $V(\bar{\theta})+\bar{\theta}$ *is positive*.

Additionally, we impose the following regularity condition:

Assumption 4 (regularity condition): The function $V(\theta_i)+\theta_i-\frac{1-F(\theta_i)}{f(\theta_i)}$

is strictly increasing over $[\underline{\theta},\bar{\theta}]$.[10]

B. Complete Information

In this section, we assume that both the seller and buyer know the quality of the match for each pairing of seller and buyer. This case serves as a benchmark because asymmetric information is not an issue.

We know that when the contract is allocated to buyer *i*, the surplus generated is $V(\theta_i)+\theta_i$ and that when the contract is not allocated, the surplus generated is zero. By Assumption 2, $V(\theta_i)+\theta_i$ is increasing in θ_i. Let $\theta_{(n)}$ represent the nth order statistic; that is, let:

$$\theta_{(n)} \equiv \max\{\theta_1, \theta_2, \ldots., \theta_n\}.$$

If $V(\theta_{(n)})+\theta_{(n)} \geq 0$, the surplus is maximized by allocating the contract to the buyer with best match quality. If $V(\theta_{(n)})+\theta_{(n)} < 0$, the surplus is maximized by not

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[10] Note that Assumption 4 is less restrictive than the monotone hazard rate condition.

allocating the contract. If the contract is allocated so as to maximize the surplus, the allocation is said to be *efficient*.

We will show that under the complete information paradigm, the seller can both allocate the contract efficiently and appropriate the entire surplus. Consider the following mechanism:

1. After observing the vector of matches ($\theta_1, \theta_2, ..., \theta_n$), the seller identifies the buyer with the best match quality (i.e., the buyer whose match quality equals $\theta_{(n)}$).

2. If $V(\theta_{(n)}) + \theta_{(n)} < 0$, the seller retains the contract, and every agent earns zero utility.

3. If $V(\theta_{(n)}) + \theta_{(n)} \geq 0$, the seller approaches the buyer identified in (1) and offers the contract at a price of $\theta_{(n)}$. If the buyer accepts the offer, the seller earns utility of $V(\theta_{(n)}) + \theta_{(n)}$. If the buyer rejects the offer, the seller earns utility of zero. In either case, every buyer earns zero utility.

Since every buyer's reservation utility is zero and the mechanism delivers zero utility to every buyer in every case, the buyers are willing to participate in the mechanism. In other words, the mechanism is individually rational for the buyers.

The mechanism is optimal in that it maximizes the seller's expected utility. Since the mechanism allocates the contract efficiently, total surplus is maximized. In addition, if we assume the buyer accepts the offer (being indifferent between accepting and rejecting), the seller captures the entire surplus in every case. The seller can do no better without the ability to force a buyer to participate in an arrangement that would be worse than the status quo.

C. Informed Seller

In this section, we introduce an asymmetry in the information structure. It is assumed that the seller is better informed about the matches than the buyers. The seller observes the quality of the match with each of the buyers (i.e., the vector

($\theta_1, \theta_2, ..., \theta_n$)). However, the buyers do not observe the matches. Their beliefs about the matches are determined by the prior distribution F and any action taken by the seller.

Although the seller possesses all the information, the entire surplus will generally not be captured. The issue is that the buyers do not know the quality of their matches. To illustrate, suppose $\theta_{(n)} = \bar{\theta}$. Since $V(\bar{\theta}) + \bar{\theta} > 0$ (see Assumption 3), the seller approaches the buyer with the best match quality and offers the contract at a price $\bar{\theta}$. However, since the buyer does not know the quality of the match, it is unclear that that the contract is worth $\bar{\theta}$. The only clear thing is that the seller approached the buyer and therefore the match must be the highest quality (i.e., $\theta_{(n)}$). Without knowing that $\theta_{(n)} = \bar{\theta}$, the buyer is unwilling to pay $\bar{\theta}$. Consequently, the seller is unable to capture the entire surplus, $V(\bar{\theta}) + \bar{\theta}$.

Clearly, the seller would like to convey the information about the quality of the matches so that the entire surplus could be captured. A straightforward declaration is not credible (the seller would declare that $\theta_{(n)} = \bar{\theta}$ irrespective of whether or not it were true) and therefore ineffective. Any information must be transmitted via the mechanism itself. For instance, if the mechanism directs the seller to always approach the buyer with the best match, any approached buyer can infer that the quality of the match is $\theta_{(n)}$. In contrast, the buyers do not have any private information. Nothing is gained by designing a mechanism that would allow buyers to convey their information. For these reasons, we focus our attention on mechanisms in which the seller makes offers to the buyers and disregard mechanisms in which the buyers make offers to the seller (e.g., auctions).

We proceed by constructing the best take-it-or-leave-it offer sellers can implement when they are the informed party. We begin by asserting that when sellers do make an offer, they approach the buyer with the best match. There are two reasons for this. First, since $V(\theta_i)$ increases with θ_i, the sellers simply get more value from contracting with a well-matched buyer. Second, if the sellers systematically approach the buyer with the best match, the approached buyer will update his or her belief about the quality of the match accordingly. In raising the estimated quality of the match, the buyer raises his or her willingness to pay for the contract. As a result, the seller can demand a higher price.

We now address what that price should be. In the complete information case, the realized matches $(\theta_1, \theta_2, ..., \theta_n)$ determine whether the seller makes an offer and what the proposed price is if the seller makes an offer. In the informed seller case, the realized matches determine whether an offer is made but is not the proposed price. For any realization of $(\theta_1, \theta_2, ..., \theta_n)$ such that the seller does make an offer, the proposed price will be the same.

The reason the proposed price cannot vary with the realization is that the seller will want to deviate to the highest acceptable price. For instance, consider a mechanism that directs the seller to propose a price of *t'* when the realized matches are $(\theta'_1, \theta'_2, ..., \theta'_n)$ and a price of *t''* when the realized matches are $(\theta''_1, \theta''_2, ..., \theta''_n)$. If *t'' >t'*, the seller will want to deviate by proposing *t''* even when the realized matches are $(\theta'_1, \theta'_2, ..., \theta'_n)$. Since the approached buyer does not observe the matches, it will assume the realization is $(\theta''_1, \theta''_2, ..., \theta''_n)$ and be willing to pay the proposed price of *t''*.

Let *t* represent the price proposed by the seller when an offer is made. We now identify the realizations of $(\theta_1, \theta_2, ..., \theta_n)$ for which the seller approaches a buyer and proposes *t*. Since the seller always approaches the best-matched buyer, the only relevant parameter is $\theta_{(n)}$. When $V(\theta_{(n)}) + t \geq 0$, the seller prefers to make the offer; when $V(\theta_{(n)}) + t < 0$, the seller would rather retain the contract. Since t is fixed and V is increasing, there exists a threshold $\theta_*(t)$ such that when $\theta_{(n)} \geq \theta_*(t)$, the seller makes the offer but when $\theta_{(n)} < \theta_*(t)$, the seller retains the contract. We formally define this threshold as follows:

$$\theta_*(t) \equiv \begin{cases} \underline{\theta} & \text{if } V(\underline{\theta}) + t > 0 \\ \{x \in [\underline{\theta}, \overline{\theta}] : V(x) + t = 0\} & \text{if } t \in [-V(\overline{\theta}), -V(\underline{\theta})] \\ \overline{\theta} & \text{if } V(\overline{\theta}) + t < 0 \end{cases}$$

Given this threshold, we calculate the highest price an approached buyer is willing to pay. An approached buyer knows that it is the buyer with the best match and that the quality of the match is at least $\theta_*(t)$. Therefore, the expected value for the contract is equal to the expected value of the match θ_i conditional on $\theta_i \geq \theta_j$ for all $j \in \{1, 2, \ldots, n\}$ and on $\theta_i \geq \theta_*(t)$. Setting the proposed price equal to this expectation yields:

$$t(\theta_*) \equiv \frac{\int_{Q_*}^{\overline{Q}} x dF^n(x)}{1 - F^n(\theta_*)}$$

We have constructed a function that gives the minimum match quality θ_* in terms of the proposed price *t* and another function that gives the proposed price *t* in terms of the minimum match quality θ_*. It remains to identify a pair (θ_*^{IS}, t^{IS}) that is consistent with both functions. In other words, the pair (θ_*^{IS}, t^{IS}) must satisfy $\theta_*(t^{IS}) = \theta_*^{IS}$ and $t(\theta_*^{IS}) = t^{IS}$. Since θ_* (t) is a non-increasing function and t(θ_*) is a non-decreasing function, the pair (θ_*^{IS}, t^{IS}) is well defined and unique as shown in Figure 7.

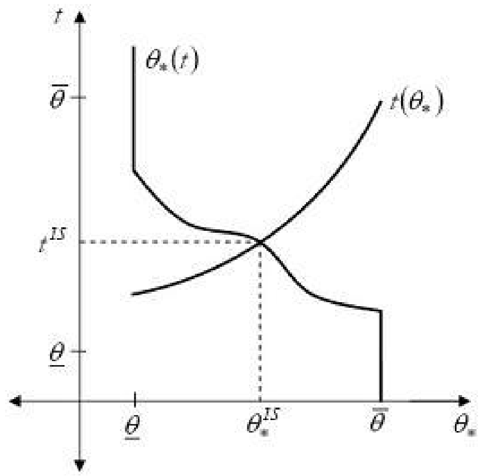

Figure 7. Best Take-It-Or-Leave-It Offer with an Informed Seller

This completes our construction of the best take-it-or-leave-it offer the seller can implement.[11] The mechanism is summarized as follows:

1. After observing the vector of matches ($\theta_1, \theta_2, ..., \theta_n$), the seller identifies the buyer with the best match quality (i.e., the buyer whose match quality equals θ(n)).

2. If $\theta_{(n)} < \theta_*^{IS}$, the seller retains the contract, and every agent earns zero utility.

3. If $\theta_{(n)} \geq \theta_*^{IS}$, the seller approaches the buyer identified in (1) and offers the contract at a price of t^{IS} . If the buyer accepts the offer, it earns utility of $\theta_{(n)} - t^{IS}$. The seller earns utility of $V(\theta_{(n)}) + t^{IS}$, and every other buyer earns zero utility. If the buyer rejects the offer, every agent earns zero utility.

The mechanism is individually rational for the buyers. Recall that every buyer's reservation utility is zero. When $\theta_{(n)} < \theta_*^{IS}$, the buyers earn zero utility and are therefore

[11] Whether or not this mechanism is optimal as defined by Myerson (1983) has not been determined yet. We have shown the mechanism is not a strong solution. However, we suspect no strong solution exists and the mechanism is a neutral optimum. Verifying this conjecture is the subject of current work.

indifferent about participating in the mechanism. When $\theta_{(n)} \geq \theta_*^{IS}$, the approached buyer earns utility of $\theta_{(n)} - t^{IS}$. Since t^{IS} may be greater than, less than, or equal to $\theta_{(n)}$, the buyer's actual utility may be positive, negative, or zero. However, the buyer's *expected* utility is zero since t^{IS} is the expected value of $\theta_{(n)}$ conditional on $\theta_{(n)} \geq \theta_*^{IS}$. It follows that the approached buyer is indifferent about accepting the offer, as well as indifferent about participating in the mechanism. Unapproached buyers earn zero utility and are therefore indifferent about participating in the mechanism as well.

The mechanism is generally not efficient. When a mutually-beneficial exchange exists (i.e., when $V(\theta_{(n)}) + \theta_{(n)} \geq 0$, the contract is allocated to the buyer with the best match, and efficiency is achieved. However, there are cases in which it would be efficient for the seller to retain the contract, but the contract is allocated anyway. That is, the frequency of trade is too high. This may occur when the (uninformed) buyer's expected value for the contract t^{IS} exceeds the realized value for the contract $\theta_{(n)}$. Since $\theta_{(n)} < t^{IS}$, it could the case that $V(\theta_{(n)}) + \theta_{(n)} < 0 \leq V(\theta_{(n)}) + t^{IS}$. The seller makes the offer because $V(\theta_{(n)}) + t^{IS} > 0$. The buyer accepts the offer because it expects to earn zero utility but then regrets the decision when it is discovered that $\theta_{(n)} - t^{IS} < 0$.

When the mechanism fails to allocate the contract efficiently, total surplus is not maximized. However, the surplus that is generated accrues to the seller in expectation. For some realizations of ($\theta_1, \theta_2, ..., \theta_n$), the seller appropriates less than the total surplus generated. For other realizations of ($\theta_1, \theta_2, ..., \theta_n$), the seller appropriates more than the total surplus generated (while the buyer earns negative utility). But on average, the seller captures the entire surplus.

D. Informed Buyer

In this section, the asymmetry in the information structure is reversed. We assume the buyers are better informed about the matches than the seller is. Each buyer observes the quality of the match with the seller. The seller does not observe the matches. The seller's belief about the matches is determined by the prior distribution *F* and the actions taken by the buyers.

This case is examined at length in Lamping (2007). Lamping shows that the seller's best strategy is to implement a first-price auction with a reserve price of:

$$\theta_*^{IB} \equiv \begin{cases} \left\{ x \in (\underline{\theta}, \overline{\theta}) : V(x) + x = \dfrac{1-F(x)}{f(X)} \right\} & \text{if } V(\underline{\theta}) + \underline{\theta} < \dfrac{1}{f(\underline{\theta})} \\ \underline{\theta} & \text{otherwise} \end{cases}$$

An auction is preferred in this setting not only because it generates competition among the buyers but also because it allows the buyers to transmit their private information through their bids. The higher the quality of a buyer's match, the higher the value for the contract, and the higher the bid. The result is that the contract is sold to the most compatible buyer at a price that is correlated with its willingness to pay for the contract.

The auction mechanism is generally not efficient. When the contract is allocated, the allocation is efficient. However, there are cases in which it would be efficient to allocate the contract, but the seller retains the contract anyway. That is, the frequency of trade is too low. This occurs because the prescribed reserve price is artificially high. Since $V(\theta_*^{IB}) + \theta_*^{IB} > 0$, it is possible to have $\theta_{(n)} < \theta_*^{IB}$ *but* $V(\theta_{(n)}) + \theta_{(n)} > 0$. That is, a mutually-beneficial exchange exists $V(\theta_{(n)}) + \theta_{(n)} > 0$ but does not occur because the most compatible buyer's value for the contract ($\theta_{(n)}$) falls short of the reserve price (θ_*^{IB}).

When the auction fails to allocate the contract efficiently, total surplus is not maximized. Moreover, only a portion of the surplus generated accrues to the seller. Because the buyers make the offers, they generally bid less than their value for the contract. Hence, any buyer whose match quality exceeds θ_*^{IB} earns positive utility in expectation. The seller appropriates less than the total surplus for every realization of $(\theta_1, \theta_2, ..., \theta_n)$ and in expectation.[12]

E. Conclusion

We have shown that the optimal mechanism depends on which side of the market is better informed about the quality of the matches. When the seller is the informed party, the seller's best strategy is to approach the most compatible buyer and make a take-it-or-leave-it offer. When the buyers are better informed, the seller's best strategy is to implement a first-price auction.

One of the limitations of this study is that it considers only those cases in which one side of the market is perfectly informed. In reality, neither the seller nor the buyer is likely to be perfectly informed, but each party may have an impression (i.e., observe a signal) about the quality of the match. We would like to examine this case in the future so as to identify how the optimal mechanism would balance the advantages of a take-it-or-leave-it offer with those of a first-price auction.

[12] There are two exceptions. When $\theta_{(n)} = \theta_*^{IB}$, the seller earns $V(\theta_*^{IB}) + \theta_*^{IB}$, capturing the entire surplus. When $\theta_{(n)}$ satisfies $V(\theta_{(n)}) + \theta_{(n)} \leq 0$, the seller retains the contract, earning zero utility and trivially capturing the entire surplus.

VI. Summary, Conclusions and Issues for Further Research

The Department of Defense (DoD) participates in procurement transactions that involve several buyer-seller environments. As a consumer of standard commercial commodities, such as pencils and paper, it participates in markets with many buyers and sellers, though the size of defense purchases often makes DoD an atypical consumer in these markets. As a consumer of specialized defense products, DoD operates as single buyer with anywhere from a single to several potential suppliers, depending on the uniqueness of the defense product.

Economic theory suggests that traditional markets are most effective when there are many potential buyers and sellers, and products are relatively standardized. In traditional markets, competition between both buyers and sellers ensures that the market establishes an efficient price to balance supply and demand. Bargaining generally characterizes situations in which markets are thin and there are few buyers and sellers. Reverse auctions are increasingly used in cases in which there is only one buyer and several sellers. Given the diversity of procurement environments facing DoD, one would expect to see DoD exploiting a variety of transaction mechanisms, including traditional markets, bargaining and reverse auctions.

This research has described the current application of reverse auctions in the federal procurement process, focusing primarily on the Department of Defense. In general, reverse auctions have been limited to procurement actions involving relatively standard price-driven commercial products—products typically purchased through traditional competitive markets. It appears that DoD has substituted reverse auctions for the market research required in the standard DoD procurement processes; the auction service providers are replacing federal procurement agents in advertising the procurement action and soliciting bids from competing suppliers.

Cost estimates indicate that DoD has realized substantial savings by implementing reverse auctions, as measured by comparing the independent government price estimate to the final auction price. It appears these savings primarily reflect an increase in competition for these solicitations. As competition increases, DoD is more likely to find a lower cost provider and sellers are likely to offer more competitive prices. Presumably, DoD could realize similar savings if it expanded its market research in the traditional procurement process; the commercial RA providers simply offer a cost-effective means to accomplish this goal.

As DoD explores expanding its use of reverse auctions and other procurement mechanisms into areas where DoD is the single buyer and suppliers might vary from one to many, information asymmetries are a critical factor. As such, this research has explored two scenarios involving information asymmetries: reverse auctions in which the buyer and sellers are imperfectly informed about tradeoffs between price and other product characteristics (technical, schedule and contractor capabilities) and transactions in which the quality of fit between buyers and sellers is uncertain but affects the transaction's value. The research showed potential performance improvements when decentralized trade-off information is centralized through the two-stage Iterated Information Aggregation Auction (I^2A^2). The research also developed optimal mechanisms under different information environments for transactions in which the quality of buyer/seller fit is important; transactions in which both parties know the quality of fit and transactions in which only one party (either the buyer of sellers) know the quality of fit.

The research reported here represents the early stages of research addressing how DoD can better structure its procurement transactions, incorporating recent developments in the economics literature regarding information asymmetries and mechanism design. There are several extensions to this research. The I^2A^2 mechanism shows promise in theory; it would be useful to conduct economics experiments using this mechanism to see if actual performance corresponds to the theoretical predictions. This iterated information aggregation approach could be extended to situations with greater uncertainty (e.g., where the buyer does not know the seller's cost function) and to centralize other information asymmetries.

It is important to note that this two-stage auction is conceptually different than the two-stage auctions currently supported by FedBid and USAAVE. FedBid and USAAVE support two-stage auctions in which the first stage involves seller prequalification (as opposed to information aggregation); only some of the initial participants are invited to bid in the second round and price becomes the dominant decision criteria. The alternative to a prequalification stage is to conduct the procurement in a single stage, using a multi-criteria scoring rule to aggregate price and seller qualifications when selecting the winning bid. Further research could help determine the relative performance of these two competing approaches.

These research topics, among others, would help move reverse auctions in DoD beyond a substitute for market research and into more appropriate reverse auction settings with a single buyer and multiple sellers. In addition, this line of research could begin addressing DoD's bargaining mechanisms for transactions involving a single buyer and single seller. Is DoD appropriately structuring its bargaining and contractual relationships considering the incentive and information asymmetries involved in these relationships? Expanding this research along these lines would address the full range of DoD's procurement relationships.

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Appendix A. FedBid Auction Results By NAICS Code

NAICS Code	Total $ Value	# of Auctions
10—Weapons	$554,200	17
12—Firing/Targeting Control Equipment	$2,099,228	17
13—Ammunition and Explosives	$34,651,901	506
15—Aircraft and Airframe Structural Components	$8,763	2
16—Aircraft Components and Accessories	$368,422	11
17—Aircraft Launching, Landing, and Ground Handling Equipment	$83,563	4
18—Space Vehicles	$250,098	10
19—Ships, Small Craft, Pontoons, and Floating Docks	$44,968	2
20—Ship and Marine Equipment	$2,788,571	121
23—Ground Effect Vehicles, Motor Vehicles, Trailers, and Cycles	$37,087,642	82
24—Tractors	$585,789	9
25—Vehicular Equipment Components	$2,399,645	92
26—Tires and Tubes	$3,707	1
28—Engines, Turbines, and Components	$93,321	3
29—Engine Accessories	$13,109	3
30—Mechanical Power Transmission Equipment	$53,183	5
31—Bearings	$9,760	1
32—Woodworking Machinery and Equipment	$102,318	8
34—Metalworking Machinery	$362,799	32
35—Service and Trade Equipment	$847,296	71
36—Special Industry Machinery	$1,810,460	146
37—Agricultural Machinery and Equipment	$190,192	6
38—Construction, Mining, Excavating, and Highway Maintenance Equipment	$2,463,516	25
39—Materials Handling Equipment	$2,109,289	46
40—Rope, Cable, Chain, and Fittings	$26,757	2
41—Refrigeration, Air Conditioning, and Air Circulating Equipment	$20,223,969	1148
42—Fire Fighting, Rescue, and Safety Equipment; and Environmental Protection Equipment and Materials	$3,509,469	145
43—Pumps and Compressors	$115,786	9
44—Furnace, Steam Plant, and Drying Equipment	$232,686	6
45—Plumbing, Heating, and Waste Disposal Equipment	$332,227	18
46—Water Purification and Sewage Treatment Equipment	$800,384	10
47—Pipe, Tubing, Hose, and Fittings	$30,201	4
48—Valves	$21,934	3
49—Maintenance and Repair Shop Equipment	$292,149	19
51—Hand Tools	$688,410	61
52—Measuring Tools	$35,892	6
53—Hardware and Abrasives	$566,725	25
54—Prefabricated Structures and Scaffolding	$2,198,937	17
55—Lumber, Millwork, Plywood, and Veneer	$426,995	8
56—Construction and Building Materials	$724,450	30
58—Communication, Detection, and Coherent Radiation Equipment	$55,748,663	1060
59—Electrical and Electronic Equipment Components	$1,803,555	86
60—Fiber Optics Materials, Components, Assemblies, and Accessories	$445,751	16

61—Electric Wire, and Power and Distribution Equipment	$1,481,774	58
62—Lighting Fixtures and Lamps	$632,231	29
3—Alarm, Signal and Security Detection Systems	$11,826,216	296
65—Medical, Dental, and Veterinary Equipment and Supplies	$7,277,606	374
66—Instruments and Laboratory Equipment	$31,457,032	396
67—Photographic Equipment	$2,928,020	221
68—Chemicals and Chemical Products	$3,509,048	9
69—Training Aids and Devices	$1,089,371	31
70—Information Technology (ADP) Equipment (Including Firmware), Software, Supplies and Support Equipment	$532,692,444	9079
71—Furniture	$8,270,443	433
72—Household and Commercial Furnishings and Appliances	$3,342,412	157
73—Food Preparation and Serving Equipment	$1,264,194	35
74—Office Machines, Text Processing Systems and Visible Record Equipment	$8,679,210	434
75—Office Supplies and Devices	$19,296,494	865
76—Books, Maps, and Other Publications	$359,569	31
77—Musical Instruments, Phonographs, and Home-type Radios	$823,596	36
78—Recreational and Athletic Equipment	$445,603	22
79—Cleaning Equipment and Supplies	$68,041	10
80—Brushes, Paints, Sealers, and Adhesives	$40,943	4
81—Containers, Packaging, and Packing Supplies	$1,397,181	54
83—Textiles, Leather, Furs, Apparel and Shoe Findings, Tents and Flags	$1,091,170	67
84—Clothing, Individual Equipment, and Insignia	$9,153,946	105
85—Toiletries	$20,751	2
87—Agricultural Supplies	$107,918	1
88—Live Animals	$423,628	9
89—Subsistence	$2,031,537	6
91—Fuels, Lubricants, Oils, and Waxes	$42,255	1
93—Nonmetallic Fabricated Materials	$127,501	5
95—Metal Bars, Sheets, and Shapes	$298,327	7
96—Ores, Minerals, and Their Primary Products	$19,407	1
99—Miscellaneous	$4,400,679	162
B—Special Studies and Analyses	$19,931	1
C—Architect and Engineering Services—Construction	$23,718	2
D—Information Technology (IT/ADP) and Telecommunication Services	$5,340,822	26
Directed Buys—Direct Buys for Individual Buyers	$189,965,843	1302
F—Natural Resources Management	$2,335,218	3
H—Quality Control, Testing and Inspection Services	$5,016	2
J—Maintenance, Repair, and Rebuilding of Equipment	$427,208	16
M—Operation of Government-owned Facility	$786,779	39
N—Installation Equipment	$1,667,932	30
Q—Medical Services	$24,869	4
R4—Professional Service	$297,939	6
R6—Administrative Support Service	$31,098	1
R7—Management Support Service	$278,173	16
S1—Utilities	$256,295	4
S2—Housekeeping Services	$462,948	8
T—Photographic, Mapping, Printing, and Publication Services	$240,184	4
U—Education and Training Services	$1,658,763	45
V—Transportation, Travel and Relocation Services	$45,609	6

W—Lease or Rental of Equipment	$636,115	8
X—Lease or Rental of Facilities	$29,870	1
Y—Construction of Structures and Facilities	$1,100,939	44
TOTAL	**$1,037,440,499**	**18,401**

Reproduced from Brown and Ray (2007, Appendix C)

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Appendix B. USAAVE Reverse Auction Savings

USAAVE REVERSE AUCTION SAVINGS: FY00 - FY07					
(QTY) PRODUCT/ITEM	IGE	TOTAL CONTRACT PRICE	% SVGS	TOTAL SAVINGS	# OF VENDORS
(1) Ricoh Secure Fax System	$6,891.00	$5,511.00	20.03%	$1,380.00	2
(2) IBM Thinkpads	$14,000.00	$6,560.00	53.14%	$7,440.00	3
(5) IntelliFAX-2750	$2,500.00	$2,200.00	12.00%	$300.00	2
(100) Connector plugs	$118,000.00	$78,000.00	33.90%	$40,000.00	2
(20) Pentium computers/items	$46,000.00	$37,000.00	19.57%	$9,000.00	5
(10) Pentium servers	$41,000.00	$24,900.00	39.27%	$16,100.00	6
(135) Pentium computers/items	$256,500.00	$175,500.00	31.58%	$81,000.00	5
(140) Pentium minitowers/items	$266,000.00	$205,800.00	22.63%	$60,200.00	4
(40) Pentium computers/items	$60,000.00	$53,600.00	10.67%	$6,400.00	4
(1) Photo-workshop	$7,000.00	$7,000.00	0.00%	$0.00	1
(520) Pentium servers	$806,000.00	$582,400.00	27.74%	$223,600.00	6
(40) Pentium computers/items	$76,000.00	$58,800.00	22.63%	$17,200.00	5
(1) Lot Lumber	$17,000.00	$15,400.00	9.41%	$1,600.00	3
(100) Caprines (Goats/Livestock)	$13,000.00	$10,000.00	23.08%	$3,000.00	5
(1) Lexar PC Card Type II	$12,200.00	$7,600.00	37.70%	$4,600.00	5
(1) Lot Dishwasher (100 each)	$22,000.00	$15,700.00	28.64%	$6,300.00	14
(1) Lot Waterheater (100 each)	$20,000.00	$12,200.00	39.00%	$7,800.00	6
(140) Brake shoe 2530-00-602-5783	$114,100.00	$98,000.00	14.11%	$16,100.00	3
(308) Hydrolic Wrench	$434,280.00	$434,280.00	0.00%	$0.00	1
(35 - 1 Lot) Collar Assembly Part	$145,425.00	$121,500.00	16.45%	$23,925.00	7
(200 - 1 Lot) Office Supplies	$10,000.00	$6,000.00	40.00%	$4,000.00	9
(1) Lot SUN equipment	$500,000.00	$368,007.00	26.40%	$131,993.00	16
(40) Laptop computers	$186,000.00	$108,000.00	41.94%	$78,000.00	3
(1) Lot SUN equipment/Msg Sys	$230,000.00	$138,850.00	39.63%	$91,150.00	3
(1) Lot Appliances (Washer/Dryer)	$42,000.00	$33,600.00	20.00%	$8,400.00	8
(109 - 1 Lot) Desktop Computers	$197,000.00	$115,000.00	41.62%	$82,000.00	4
(1) Lot Paper	$43,000.00	$37,328.00	13.19%	$5,672.00	22

(1) Lot Sun Equipment & Services	$1,847,000.00	$1,717,500.00	7.01%	$129,500.00	9
(1) Lot Sun Equipment & Services	$1,052,000.00	$959,000.00	8.84%	$93,000.00	4
(1) Lot Eyepiece Assembly	$550,000.00	$261,500.00	52.45%	$288,500.00	2
(1) Lot Modular Office Furniture	$24,000.00	$17,400.00	27.50%	$6,600.00	3
(1) Lot Computer Systems	$149,000.00	$149,000.00	0.00%	$0.00	4
(1) Lot Wood Chips	$29,000.00	$25,000.00	13.79%	$4,000.00	4
(1) Lot Modular Office Furniture	$91,300.00	$69,500.00	23.88%	$21,800.00	4
(1) Lot Refrigeration Equipment	$36,000.00	$27,433.32	23.80%	$8,566.68	5
(1) Lot Pump Assembly	$522,750.00	$425,850.00	18.54%	$96,900.00	6
(370) Desktop PCs—Energy Dept	$592,370.00	$388,500.00	34.42%	$203,870.00	4
(1) Lot Dual-line Phones	$19,500.00	$17,100.00	12.31%	$2,400.00	5
(1) Lot Metal Desks	$53,000.00	$36,900.00	30.38%	$16,100.00	2
(6) HAZMAT Storage Buildings	$42,000.00	$28,770.00	31.50%	$13,230.00	5
(1) Lot Projectors, Screens, etc.	$34,000.00	$28,550.00	16.03%	$5,450.00	5
(62) Monitors	$99,200.00	$85,250.00	14.06%	$13,950.00	9
(1) Lot Desktop Computers	$2,200,000.00	$1,800,000.00	18.18%	$400,000.00	4
(154) Desktop Pentium III	$211,971.76	$160,160.00	24.44%	$51,811.76	9
(137) Antennas, AS-3244/TS	$164,400.00	$164,400.00	0.00%	$0.00	3
(1) Lot Eyepiece Assembly	$421,000.00	$421,000.00	0.00%	$0.00	2
(6000) Hose Clamps	$25,500.00	$21,000.00	17.65%	$4,500.00	4
(50) Contract Closeout Services	$10,000.00	$4,450.00	55.50%	$5,550.00	5
(1) Lot Desktop/Laptop Computers	$389,000.00	$353,000.00	9.25%	$36,000.00	6
(1) Lot Desktop Computers	$95,200.00	$83,500.00	12.29%	$11,700.00	3
(1) Lot Objective Mount Assembly	$228,000.00	$228,000.00	0.00%	$0.00	2
(1) Lot Battery Chargers	$263,500.00	$160,000.00	39.28%	$103,500.00	5
(100) Contract Closeout Services	$25,000.00	$8,000.00	68.00%	$17,000.00	8
(1) Lot Objective Mount Assembly	$497,500.00	$497,500.00	0.00%	$0.00	2
(1) Lot Water Safety Promo Items	$36,000.00	$36,000.00	0.00%	$0.00	6
(1) Lot Leveling Jacks	$159,600.00	$159,600.00	0.00%	$0.00	3
(1) Lot Appliances	$330,000.00	$270,000.00	18.18%	$60,000.00	6
(1) Lot Loudspeakers	$1,863,190.00	$963,190.00	48.30%	$900,000.00	4
(1) Lot Hydraulic Components	$630,000.00	$305,000.00	51.59%	$325,000.00	6
(1) Lot Floor Polish	$7,500.00	$5,000.00	33.33%	$2,500.00	6
(1) Lot Vapor Protective Suits	$8,100.00	$5,300.00	34.57%	$2,800.00	4
(1) Lot Vinson Test Set	$355,000.00	$203,000.00	42.82%	$152,000.00	5
(1) Lot Camera Components	$15,000.00	$10,900.00	27.33%	$4,100.00	4

(1) Lot Notebooks, CPUs & Monitors	$61,648.00	$47,748.00	22.55%	$13,900.00	5
(1) Lot HP Laser Printers 1200N	$17,250.00	$16,050.00	6.96%	$1,200.00	2
(1600) Desktop computers	$1,920,000.00	$1,440,000.00	25.00%	$480,000.00	6
(200) Computer Monitors	$25,000.00	$22,000.00	12.00%	$3,000.00	6
(1) Lot Adapter Antenna	$191,100.00	$118,100.00	38.20%	$73,000.00	5
(1) Lot CPUs and Notebooks	$1,881,059.00	$1,084,059.00	42.37%	$797,000.00	8
(1) Lot Transformer Assembly	$420,000.00	$195,000.00	53.57%	$225,000.00	4
(381) Mounting Bracket Assembly	$156,210.00	$53,340.00	65.85%	$102,870.00	4
(1) Lot Removable Canopy	$1,320,000.00	$1,100,000.00	16.67%	$220,000.00	5
(179) 2KW Diesel Engines	$250,600.00	$232,700.00	7.14%	$17,900.00	4
(53) 3KW Diesel Engines	$79,500.00	$60,950.00	23.33%	$18,550.00	4
(1) Lot Intermediate Power Assembly	$337,280.00	$150,280.00	55.44%	$187,000.00	4
(1) Lot Computers	$140,000.00	$95,000.00	32.14%	$45,000.00	2
(2465) PIN	$3,327.75	$2,218.50	33.33%	$1,109.25	4
(1) Lot Removable Canopy	$240,000.00	$195,000.00	18.75%	$45,000.00	4
(1600) Antenna Adapter	$160,000.00	$104,000.00	35.00%	$56,000.00	4
(1) Lot Transformer Assembly	$55,000.00	$38,000.00	30.91%	$17,000.00	4
(57) Mark 124 Warheads	$114,000.00	$113,430.00	0.50%	$570.00	2
(1) Lot Notebooks/Laser Printers	$875,000.00	$515,000.00	41.14%	$360,000.00	8
(1600) Antenna Adapter	$160,000.00	$88,000.00	45.00%	$72,000.00	4
(235) Displacement Gyroscopes	$1,903,500.00	$1,257,250.00	33.95%	$646,250.00	3
(1) Lot Cable Switch Assembly	$200,000.00	$127,500.00	36.25%	$72,500.00	2
(1) Lot Coupler, Rotary Radio	$690,000.00	$680,000.00	1.45%	$10,000.00	2
(1) Lot Aluminum Benches	$10,000.00	$4,800.00	52.00%	$5,200.00	4
(1) Lot Patriot Missile Spares	$2,500,000.00	$1,568,000.00	37.28%	$932,000.00	3
(1) Lot Lawn Mowers	$19,000.00	$19,000.00	0.00%	$0.00	6
(1) Lot Vacuum Cleaners	$27,500.00	$20,500.00	25.45%	$7,000.00	5
(1) Lot Pagers	$2,500.00	$800.00	68.00%	$1,700.00	3
(1) Lot Circuit Card Assembly	$36,000.00	$11,400.00	68.33%	$24,600.00	4
(1) Lot Quick Erect Antenna Mast	$4,500,000.00	$2,205,000.00	51.00%	$2,295,000.00	5
(1) Lot Generator Air Coolers	$120,000.00	$90,000.00	25.00%	$30,000.00	5
(1) Lot PC/Notebooks	$65,600.00	$65,600.00	0.00%	$0.00	12
(1) Lot Telephone Circuit Trunk Jack	$90,000.00	$90,000.00	0.00%	$0.00	2
(1) Lot Refrigerators	$52,000.00	$44,600.00	14.23%	$7,400.00	3
(100) ea 3KW Diesel Engines	$120,000.00	$120,000.00	0.00%	$0.00	4
(1) Lot Circuit Card Assembly	$93,400.00	$82,000.00	12.21%	$11,400.00	4
(1) Lot Intercomm Set Control	$112,500.00	$95,700.00	14.93%	$16,800.00	3
(1) Lot PCs/Notebooks/Monitors	$300,000.00	$235,000.00	21.67%	$65,000.00	12

(100) ea 3KW Diesel Engines	$140,000.00	$140,000.00	0.00%	$0.00	4
(1) Lot Circuit Card Assembly	$400,000.00	$220,000.00	45.00%	$180,000.00	5
(1) Lot Movable Canopy	$1,165,000.00	$870,000.00	25.32%	$295,000.00	4
(1) Lot Desktop PC/Notebooks	$1,500,000.00	$1,089,000.00	27.40%	$411,000.00	12
(1) Lot Desktop PC/Notebooks	$1,001,150.00	$671,150.00	32.96%	$330,000.00	11
(1) Lot Computer HW/SW & Furniture	$498,782.00	$264,782.00	46.91%	$234,000.00	9
(300) ea 3KW Diesel Engines	$450,000.00	$435,000.00	3.33%	$15,000.00	4
(160) ea 2KW Diesel Engines	$264,000.00	$230,400.00	12.73%	$33,600.00	4
Desktop/Notebooks	$241,500.00	$220,000.00	8.90%	$21,500.00	12
(295) ea 2KW Diesel Engines	$501,500.00	$445,450.00	11.18%	$56,050.00	4
(270) ea 3KW Diesel Engines	$405,000.00	$402,300.00	0.67%	$2,700.00	4
(1) Lot RF Tray Assembly	$1,675,000.00	$1,025,000.00	38.81%	$650,000.00	3
(1) Lot Circuit Card Assembly	$76,850.00	$38,100.00	50.42%	$38,750.00	9
(1) Lot Integrated Computer System	$50,950.00	$50,500.00	0.88%	$450.00	6
(1) Lot Patriot Missile Spares	$1,115,000.00	$1,102,500.00	1.12%	$12,500.00	2
(1) Lot Battery Housing Assembly	$2,000,000.00	$1,280,000.00	36.00%	$720,000.00	5
(1) Lot Transformer Assembly	$406,000.00	$384,500.00	5.30%	$21,500.00	2
(1) Lot Locking Devise	$20,925.00	$19,725.00	5.73%	$1,200.00	3
(1) Lot NTDR Cables	$88,000.00	$60,100.00	31.70%	$27,900.00	2
(1) Lot Mounting Brackets	$500,000.00	$280,000.00	44.00%	$220,000.00	5
(200) ea 2KW Diesel Engine	$360,000.00	$294,000.00	18.33%	$66,000.00	4
(200) ea 3KW Diesel Engine	$340,000.00	$319,000.00	6.18%	$21,000.00	4
(1) Lot Monitors	$395,800.00	$395,800.00	0.00%	$0.00	2
(1) Lot Telephone Line Jacks	$1,929,350.00	$1,524,097.00	21.00%	$405,253.00	3
(500) ea Desktop Computers	$700,000.00	$605,000.00	13.57%	$95,000.00	4
(48) ea Laptop Computers	$105,600.00	$71,520.00	32.27%	$34,080.00	4
(1) Lot Enhanced Power Adapter	$1,920,000.00	$1,790,000.00	6.77%	$130,000.00	4
(1) Lot TA312 Telephone	$139,000.00	$113,200.00	18.56%	$25,800.00	4
(1) Lot Bracket Assembly	$145,000.00	$90,000.00	37.93%	$55,000.00	5
(1) Lot Desktops/Notebooks	$392,000.00	$335,000.00	14.54%	$57,000.00	12
(1) Lot Desktops/Notebooks	$1,053,000.00	$825,000.00	21.65%	$228,000.00	12
(1) Lot Circuit Card Assembly	$120,000.00	$48,750.00	59.38%	$71,250.00	5
(1) Lot J10077 Distribution Box	$864,000.00	$310,000.00	64.12%	$554,000.00	6
(1) Lot Circuit Card Assembly	$2,815,000.00	$310,000.00	88.99%	$2,505,000.00	9
(1) Lot Spares for Countermeasure	$20,000,000.00	$9,013,988.00	54.93%	$10,986,012.00	3
(1) Lot Spares for Countermeasure	$4,000,000.00	$3,999,999.00	0.00%	$1.00	2
(1) Lot M-172 Boom Microphone	$503,000.00	$319,000.00	36.58%	$184,000.00	3
(1) Lot Ft Mon Construction	$675,000.00	$562,000.00	16.74%	$113,000.00	11

(1) Lot Mechanical Scanners	$250,000.00	$249,500.00	0.20%	$500.00	2
(1) Lot Telephone Circuit Trunk Jack	$307,000.00	$140,800.00	54.14%	$166,200.00	3
(1) Lot TA-1/PT Telephone Set	$1,631,708.00	$1,070,000.00	34.42%	$561,708.00	2
(1) Lot Circuit Card Assembly	$285,500.00	$172,000.00	39.75%	$113,500.00	4
(1) Lot Radio Set Control Assembly	$2,450,000.00	$2,450,000.00	0.00%	$0.00	3
(1) Lot PL1408 Circuit Card Assembly	$1,925,000.00	$1,199,000.00	37.71%	$726,000.00	16
(1) Lot PL1403 Circuit Card Assembly	$1,800,000.00	$689,000.00	61.72%	$1,111,000.00	15
(1) Lot Signal Scanner	$420,000.00	$270,000.00	35.71%	$150,000.00	3
(1) Lot NVD CID Tape	$857,500.00	$500,500.00	41.63%	$357,000.00	2
(108) ea 2 KW Diesel Engine	$183,600.00	$160,920.00	12.35%	$22,680.00	2
(1) Lot Patriot Spares	$572,000.00	$572,000.00	0.00%	$0.00	2
(166) ea 3 KW Diesel Engine	$282,200.00	$272,240.00	3.53%	$9,960.00	2
(1) Lot Electrical Arrester	$500,000.00	$402,800.00	19.44%	$97,200.00	5
(1) Lot M175A, Microphone Capacitor	$1,520,000.00	$1,190,000.00	21.71%	$330,000.00	2
(1) Lot Building 603 Warehouse	$1,250,000.00	$1,250,000.00	0.00%	$0.00	8
(115) ea 2KW Diesel Engines	$195,500.00	$171,350.00	12.35%	$24,150.00	2
(1) Lot Feed-horn Assembly	$250,000.00	$193,700.00	22.52%	$56,300.00	4
(1) Lot Desktop/Notebooks	$1,633,000.00	$1,360,000.00	16.72%	$273,000.00	17
(1) Lot Bldg 907 Warehouse	$700,000.00	$697,000.00	0.43%	$3,000.00	5
(204) ea 3 KW Diesel Engines	$357,000.00	$334,560.00	6.29%	$22,440.00	2
(1) Lot Power Supply	$2,902,000.00	$2,138,000.00	26.33%	$764,000.00	7
(1) Lot J10077 Distribution Box	$564,000.00	$469,000.00	16.84%	$95,000.00	7
(1) Lot Motor, Alternating	$100,000.00	$77,000.00	23.00%	$23,000.00	2
(1) Lot Power Supply Repair	$33,000.00	$5,000.00	84.85%	$28,000.00	7
(1) Lot Power Supply	$107,000.00	$47,000.00	56.07%	$60,000.00	6
(1) Lot Digital Topographical Spt Equip	$410,000.00	$405,500.00	1.10%	$4,500.00	3
(1) Lot Telephone Sets	$3,311,000.00	$2,686,000.00	18.88%	$625,000.00	5
(115) ea Diesel Engines	$189,750.00	$171,350.00	9.70%	$18,400.00	2
(451) ea Diesel Engines	$789,250.00	$739,640.00	6.29%	$49,610.00	2
(1) Lot Cable Assemblies, CX11230A/G	$11,250,000.00	$8,250,000.00	26.67%	$3,000,000.00	4
(1) Lot Cable Assemblies, CX-13404	$70,000.00	$49,000.00	30.00%	$21,000.00	6
(1) Lot AN/ARN-98B Amplifier	$335,400.00	$173,400.00	48.30%	$162,000.00	8
(1) Lot Amplifier Mixer Module	$687,000.00	$479,000.00	30.28%	$208,000.00	8
(1) Lot CISCO Computer Equip Repair	$6,200,000.00	$5,740,000.00	7.42%	$460,000.00	9
(1) Lot Fuel Pumps	$390,000.00	$330,000.00	15.38%	$60,000.00	3
(1) Lot Starter Engines	$80,000.00	$69,750.00	12.81%	$10,250.00	4

(1) Lot Amplifier Mixer Module	$119,000.00	$94,000.00	21.01%	$25,000.00	4
(1) Lot Radiators, 10KW Generator Set	$520,000.00	$495,000.00	4.81%	$25,000.00	5
(1) Lot Alternator/Engine—Electrical	$1,850,000.00	$780,000.00	57.84%	$1,070,000.00	4
(1) Lot Telephone Cable Assembly	$2,850,000.00	$1,214,100.00	57.40%	$1,635,900.00	18
(1) Lot SU-121/UA Optical Imagers	$801,500.00	$800,500.00	0.12%	$1,000.00	4
(1) Lot TK-17/G Tool Kit	$4,562,000.00	$4,405,000.00	3.44%	$157,000.00	6
(1) Lot Alternating Current Motors	$184,800.00	$149,800.00	18.94%	$35,000.00	2
(1) Lot John Deere Engine Starters	$300,000.00	$200,000.00	33.33%	$100,000.00	2
Grounding Kits	$1,100,000.00	$896,000.00	18.55%	$204,000.00	8
Antenna to Antenna Base Adapter	$14,000.00	$14,000.00	0.00%	$0.00	3
Post Amplifier Control Driver	$2,700,000.00	$630,000.00	76.67%	$2,070,000.00	9
Distribution Boxes	$60,200.00	$49,800.00	17.28%	$10,400.00	3
Tool Kit 105 A/G	$9,048,109.00	$4,913,109.00	45.70%	$4,135,000.00	4
TOTALS:			**31.62%**	**$48,651,681.69**	

Reproduced from Brown and Ray (2007, Appendix B)

2003 - 2008 Sponsored Research Topics

Acquisition Management

- Software Requirements for OA
- Managing Services Supply Chain
- Acquiring Combat Capability via Public-Private Partnerships (PPPs)
- Knowledge Value Added (KVA) + Real Options (RO) Applied to Shipyard Planning Processes
- Portfolio Optimization via KVA + RO
- MOSA Contracting Implications
- Strategy for Defense Acquisition Research
- Spiral Development
- BCA: Contractor vs. Organic Growth

Contract Management

- USAF IT Commodity Council
- Contractors in 21st Century Combat Zone
- Joint Contingency Contracting
- Navy Contract Writing Guide
- Commodity Sourcing Strategies
- Past Performance in Source Selection
- USMC Contingency Contracting
- Transforming DoD Contract Closeout
- Model for Optimizing Contingency Contracting Planning and Execution

Financial Management

- PPPs and Government Financing
- Energy Saving Contracts/DoD Mobile Assets
- Capital Budgeting for DoD
- Financing DoD Budget via PPPs
- ROI of Information Warfare Systems
- Acquisitions via leasing: MPS case
- Special Termination Liability in MDAPs

Human Resources

- Learning Management Systems
- Tuition Assistance
- Retention
- Indefinite Reenlistment
- Individual Augmentation

Logistics Management

- R-TOC Aegis Microwave Power Tubes
- Privatization-NOSL/NAWCI
- Army LOG MOD
- PBL (4)
- Contractors Supporting Military Operations
- RFID (4)
- Strategic Sourcing
- ASDS Product Support Analysis
- Analysis of LAV Depot Maintenance
- Diffusion/Variability on Vendor Performance Evaluation
- Optimizing CIWS Lifecycle Support (LCS)

Program Management

- Building Collaborative Capacity
- Knowledge, Responsibilities and Decision Rights in MDAPs
- KVA Applied to Aegis and SSDS
- Business Process Reengineering (BPR) for LCS Mission Module Acquisition
- Terminating Your Own Program
- Collaborative IT Tools Leveraging Competence

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